Results from Super-Kamiokande

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For the Super-K collaboration*

15-Mar-2011, Neutel11

* Thanks to many colleagues for slides; errors are all mine

The Super-Kamiokande Collaboration

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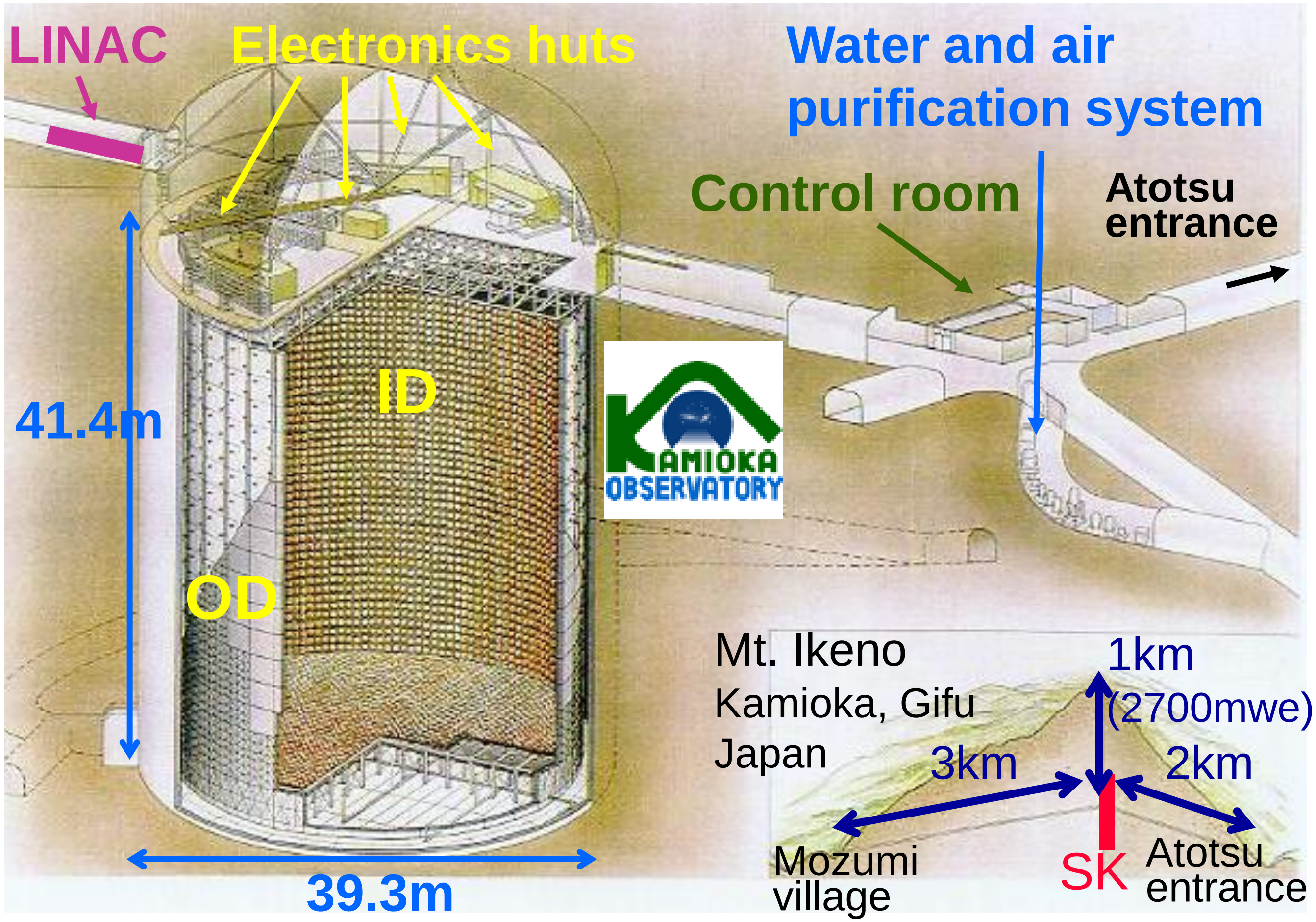
~120 collaborators
31 institutions, 6 countries

From PRD81, 092004 (2010)

Super-Kamiokande detector



50 kton water Cherenkov
22.5 kton fiducial volume
(~ 2m away from wall)

2700 m.w.e overburden
cosmic ray BG ~3 Hz

~10 Solar ν /day
~10 Atmospheric ν / day

Inner detector (ID):
~11,100 50 cm PMTs
~ 2ns timing resolution
~ 4.5MeV threshold

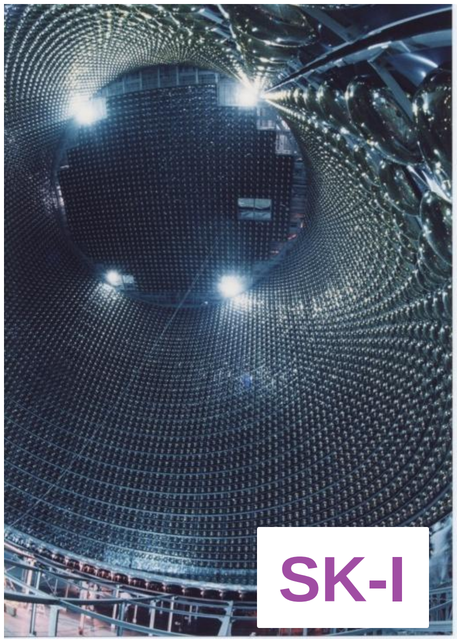
Outer detector (OD):
water layer ~ 2m thick,
1,885 20 cm PMTs

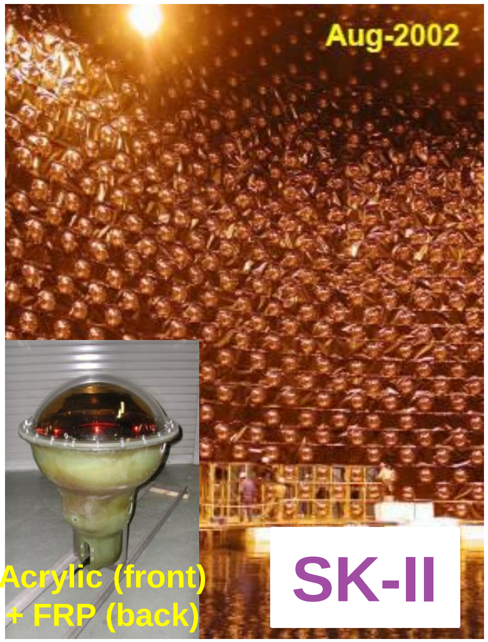
Multi-purpose observatory:
Neutrinos from Sun, atmosphere, supernova, relic SN's, astrophysical point sources, and beams from K2K and T2K
Also: search for nucleon decay, WIMPS, other exotic particles

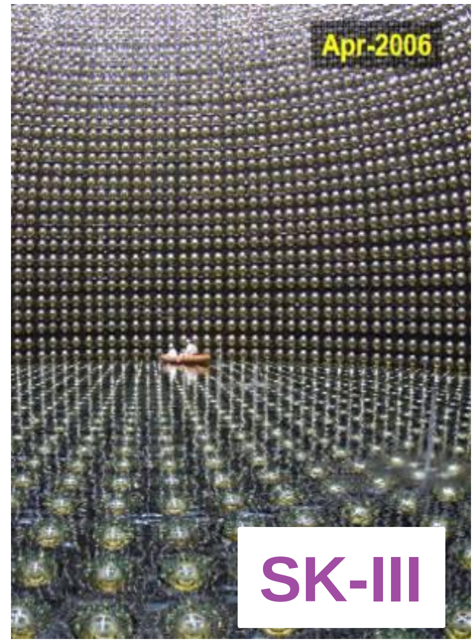
History of Super-Kamiokande

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I (Rebuild) SK-II (Rebuild) SK-III SK-IV

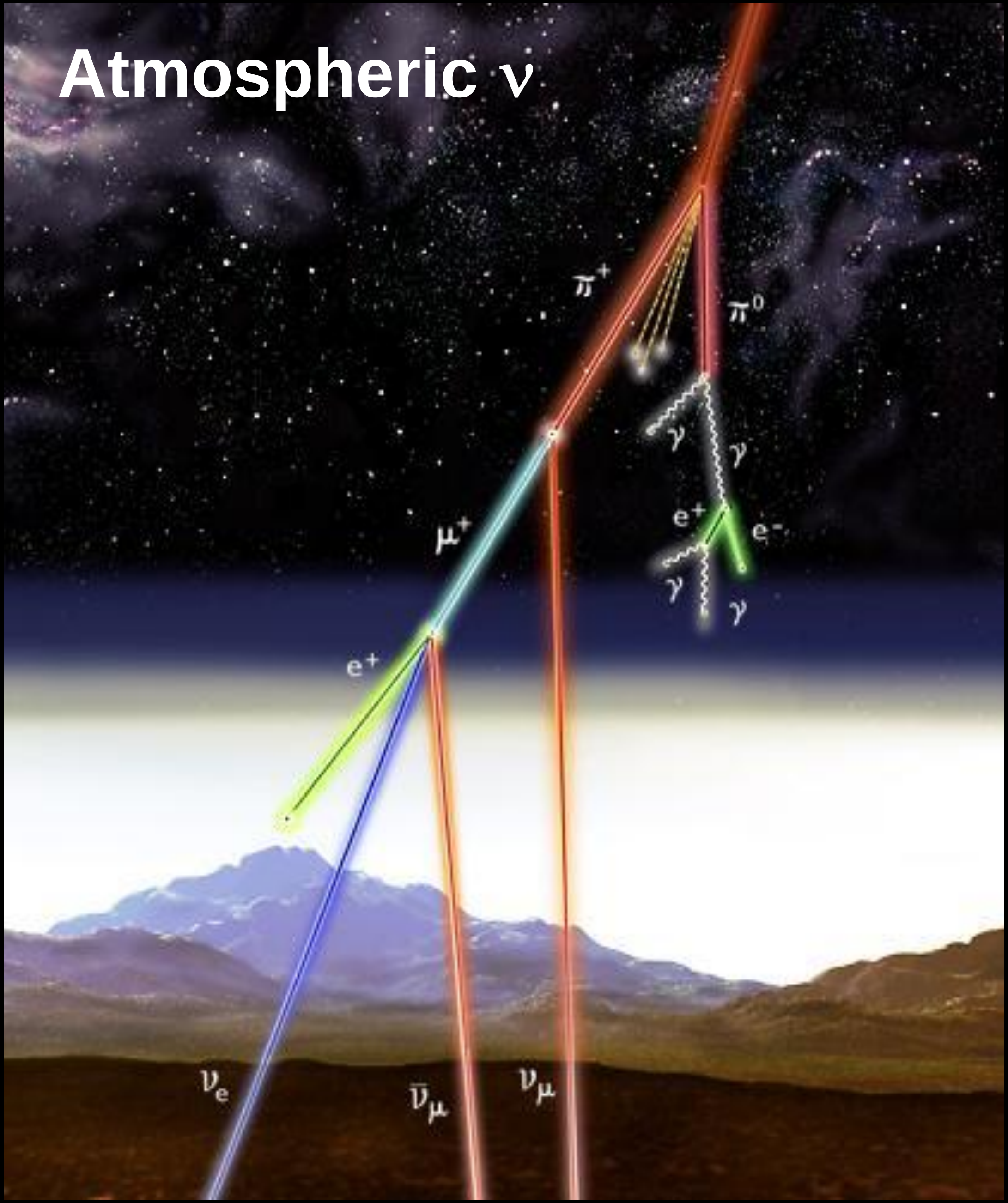






	SK-I	SK-II	SK-III	SK-IV	
	11146 ID PMTs (40% coverage)	**5182 ID PMTs (19% coverage)**	**11129 ID PMTs (40% coverage)**	**Electronics Upgrade**	
Threshold: (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				Now	Goal

Atmospheric ν



Zenith angle distributions

$\nu_\mu - \nu_\tau$ oscillation (best fit)

No oscillation + Data

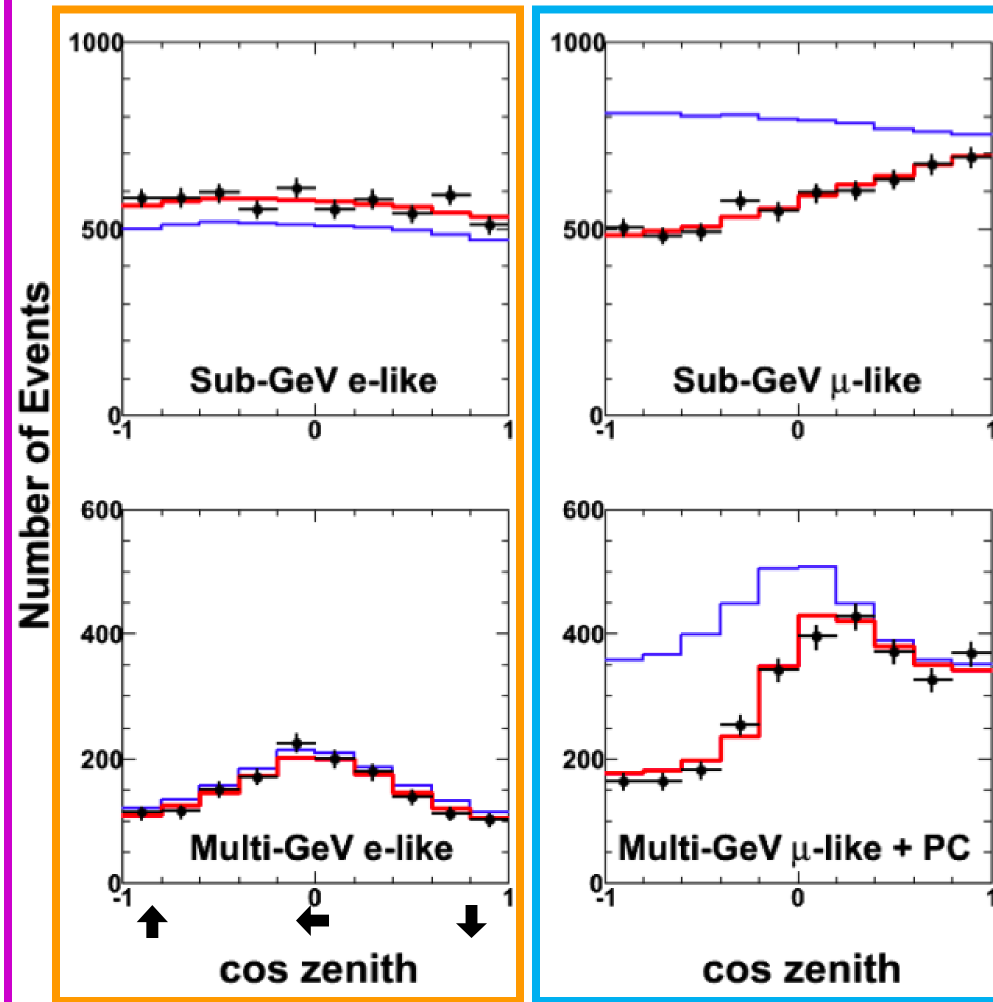
e-like

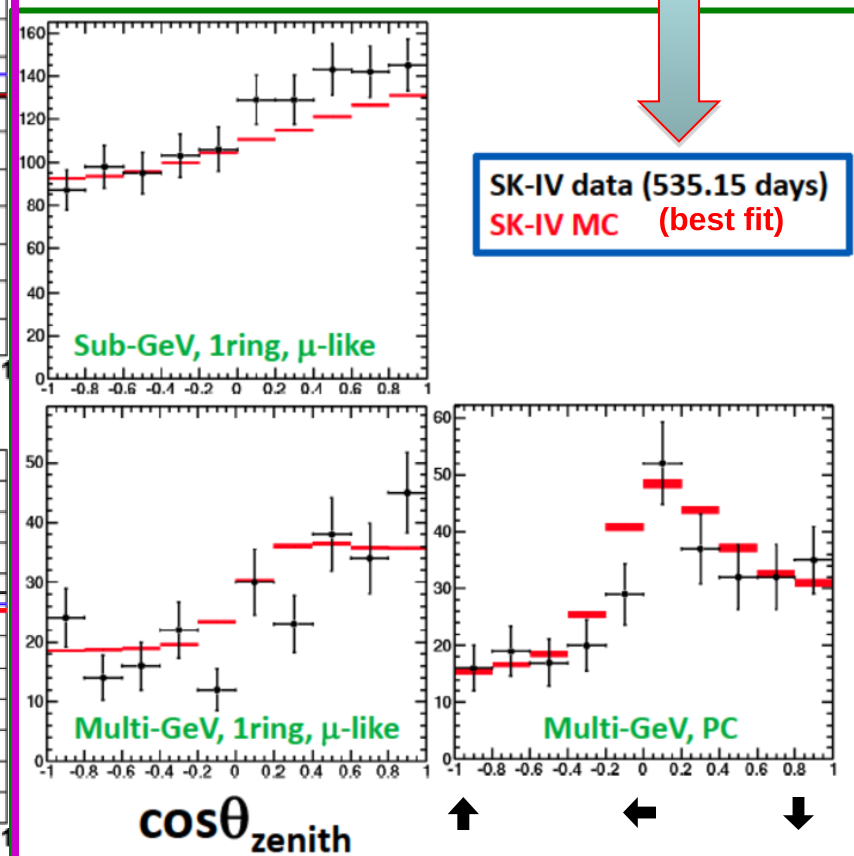
μ-like

SK-I+II+III, -IV

Preliminary

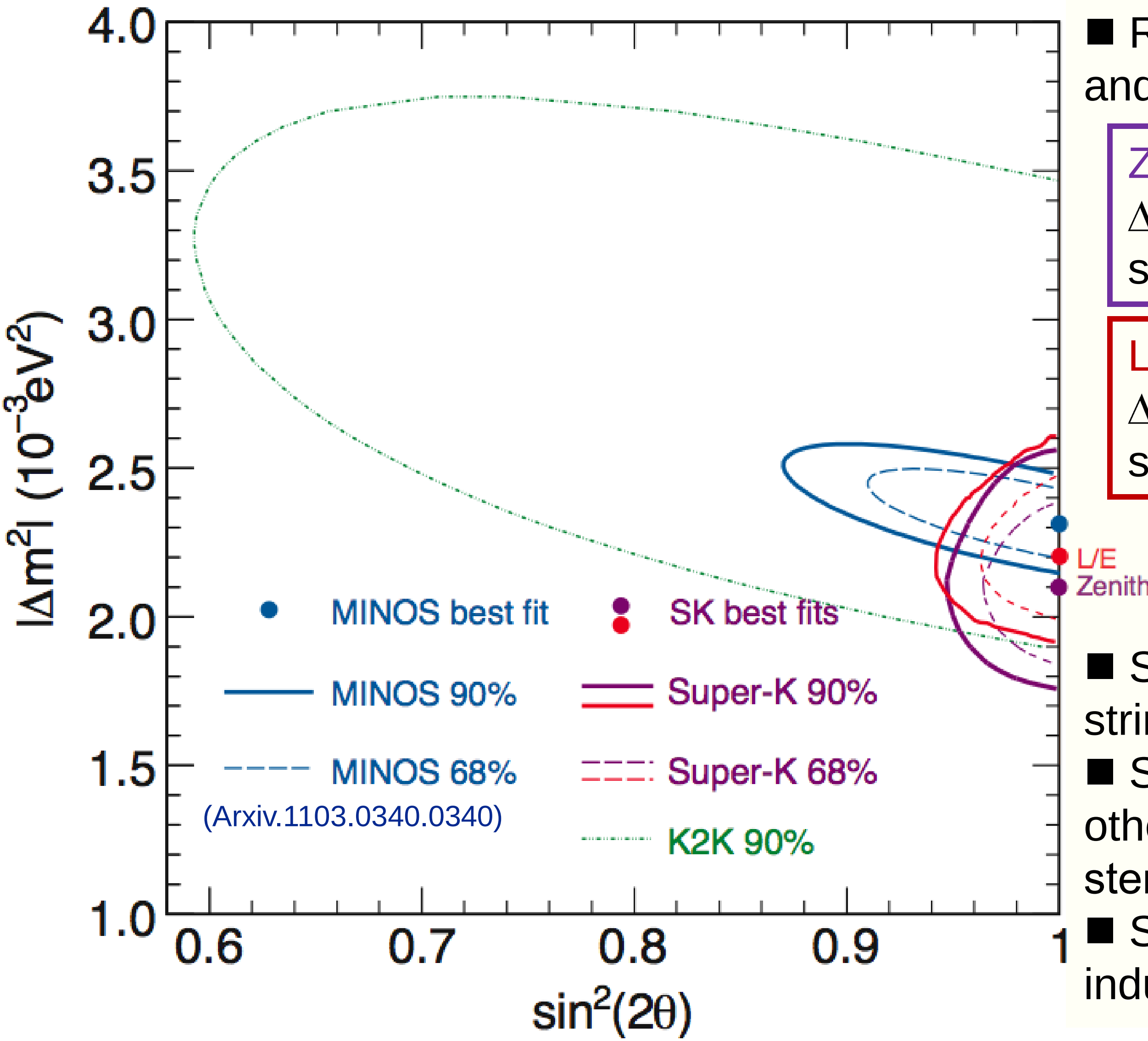
SK-I+II+III, 2806 Days





2-flavor oscillation analysis results

SK-I+II+III *Preliminary*



■ Results of SK zenith angle and L/E analyses are consistent.

Zenith Physical Region (1σ)
Δm_{23}^2=2.11+0.11/-0.19 x10^{-3}
$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

L/E Physical Region (1σ)
Δm_{23}^2=2.19+0.14/-0.13 x10^{-3}
$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

■ SK provides the most stringent limits on $\sin^2(2\theta_{23})$.
■ SK data strongly disfavor other models of disappearance, sterile n's at ~7s
■ SK can observe oscillation induced nt appearance!

Full 3-flavor oscillation analysis

- Consider matter effects and solar term simultaneously.
  - Matter effect: enhancement of ν_e expected in several GeV energy region & in Earth's core
  - θ_{13} and mass hierarchy can be studied.
- Solar term: possible enhancement of ν_e in sub-GeV region
  - θ_{23} octant degeneracy can be studied.
- Interference: phase δ_{cp} can be studied (if $\sin^2\theta_{13}$ >~0.05).

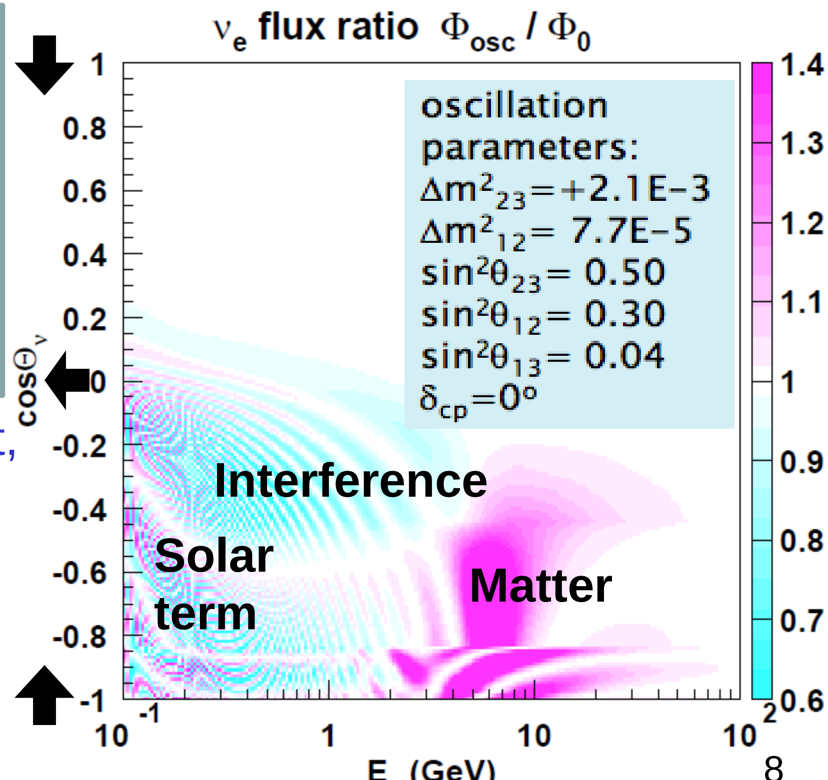
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \quad \text{Matter effect}$$
$$+\Delta_2(\Delta m^2_{12}) \quad \text{Solar term}$$
$$+\Delta_3(\theta_{13},\Delta m^2_{12},\underline{\delta}) \quad \text{Interference}$$

(ν_μ flux difference is also expected.)

Previously (PRD81, 092004): matter effect, solar term were treated separately, with approximations

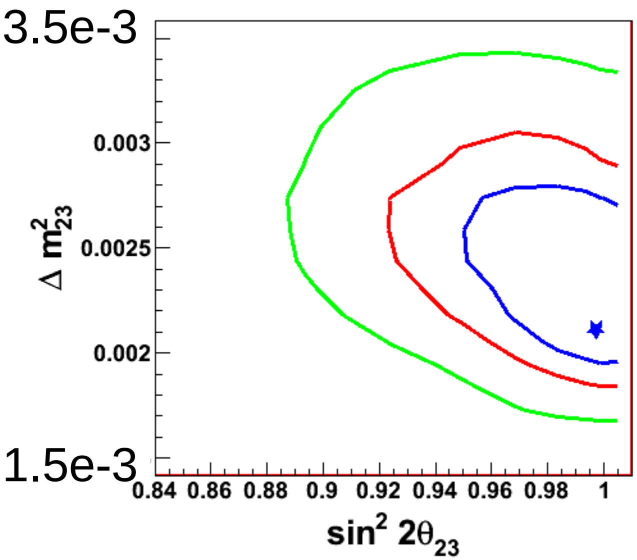
Full 3-flav. osc. Analysis: Simultaneously fit all factors; sensitive to many aspects of oscillation physics…

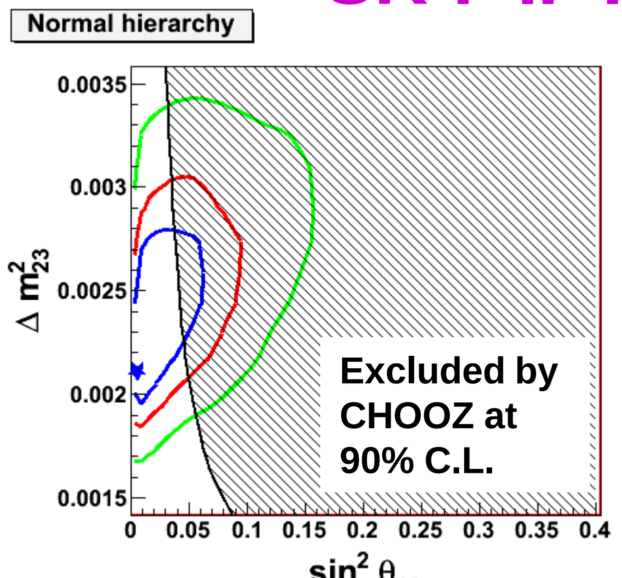


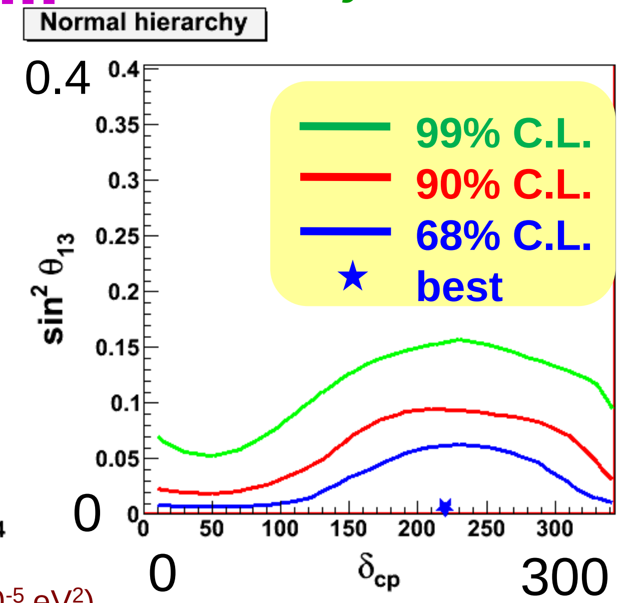
Full 3-flavor oscillation results

SK-I+II+III *Preliminary*

- Normal hierarchy -

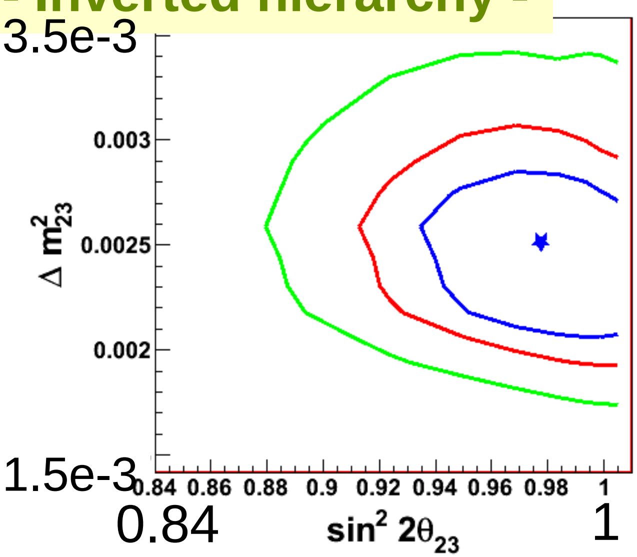


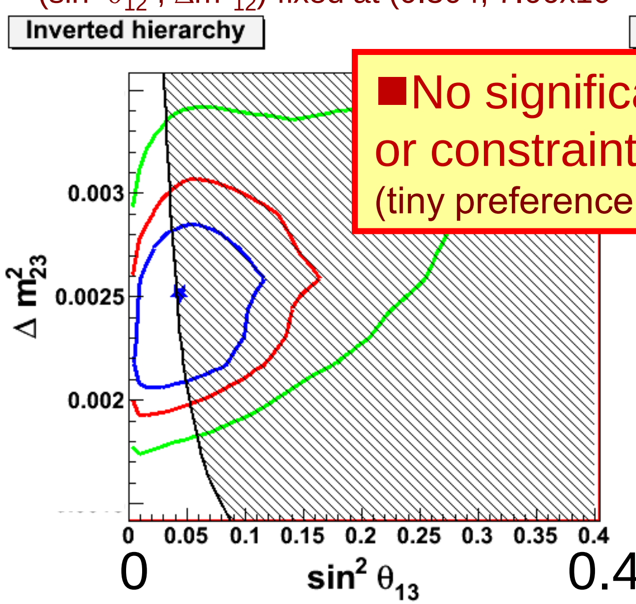


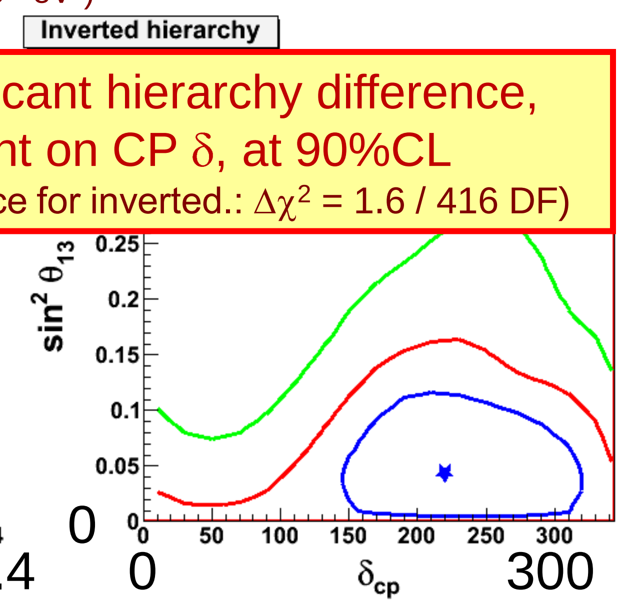


($\sin^2\theta_{12}$, Δm^2_{12}) fixed at (0.304, 7.66×10^{-5} eV^2)

- Inverted hierarchy -



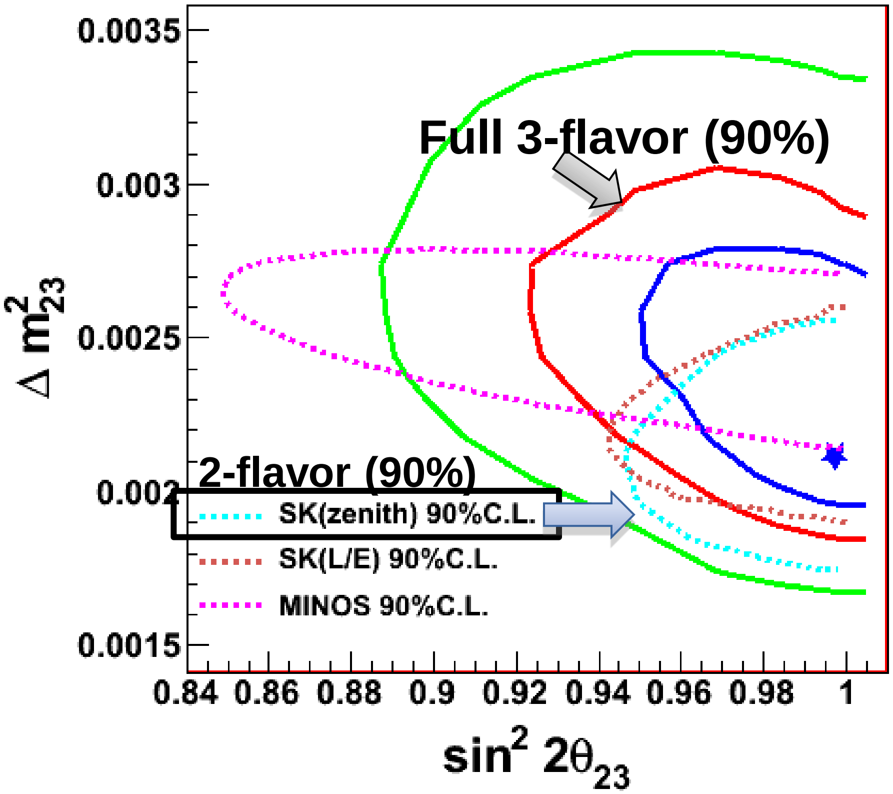




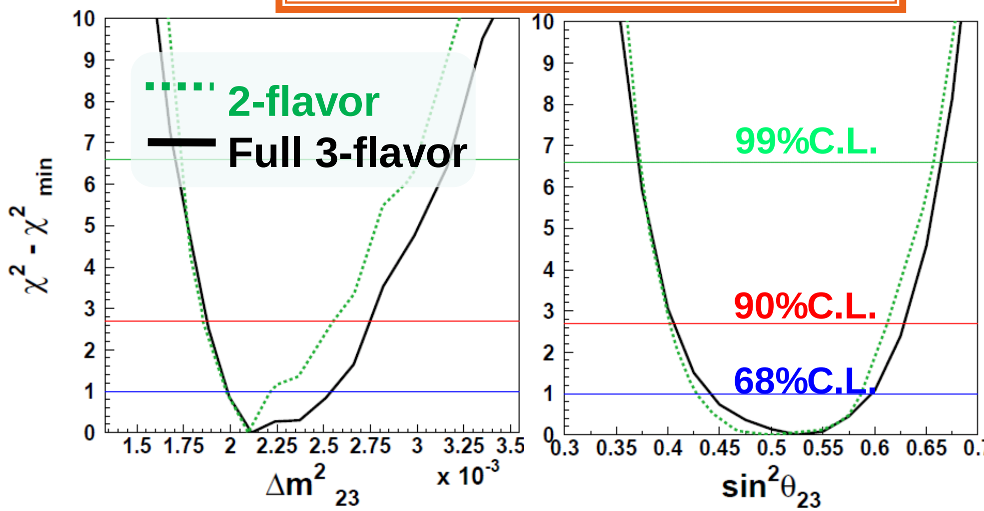
■No significant hierarchy difference, or constraint on CP δ, at 90%CL
(tiny preference for inverted.: $\Delta\chi^2 = 1.6$ / 416 DF)

Comparison with 2-flavor analysis

Normal hierarchy



$\chi^2 - \chi^2_{min}$ distributions



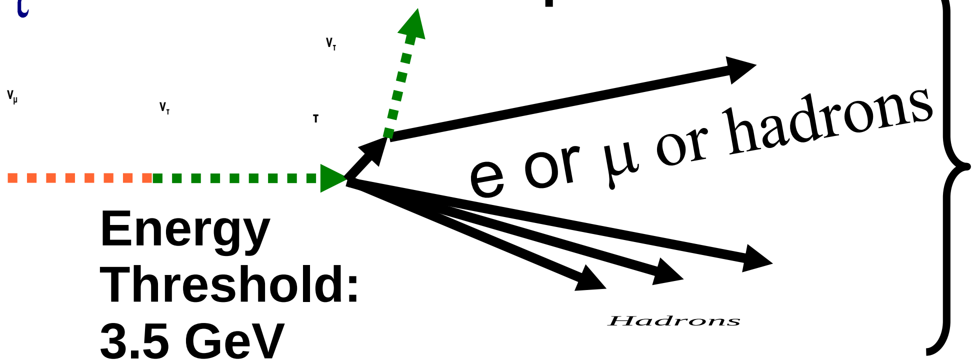
2-flavor/full flavor results consistent.
No change in best-fit $\sin^2\theta_{23}$

Δm^2_{23} allowed region is a bit larger in the full-flavor analysis, due to CP phase being taken into account.

90%C.L. allowed region (1 DOF, $\chi^2=\chi^2_{min}+2.71$)

Full 3-flavor (Normal Hier.)	*Global best-fit*
$(1.88 < \Delta m^2_{23} < 2.75)$ e-3	$(2.22 < \Delta m^2_{23} < 2.60)$ e-3
$0.406 < \sin^2\theta_{23} < 0.629$	$0.401 < \sin^2\theta_{23} < 0.615$
$(0.93 < \sin^2 2\theta_{23})$	$(0.95 < \sin^2 2\theta_{23})$

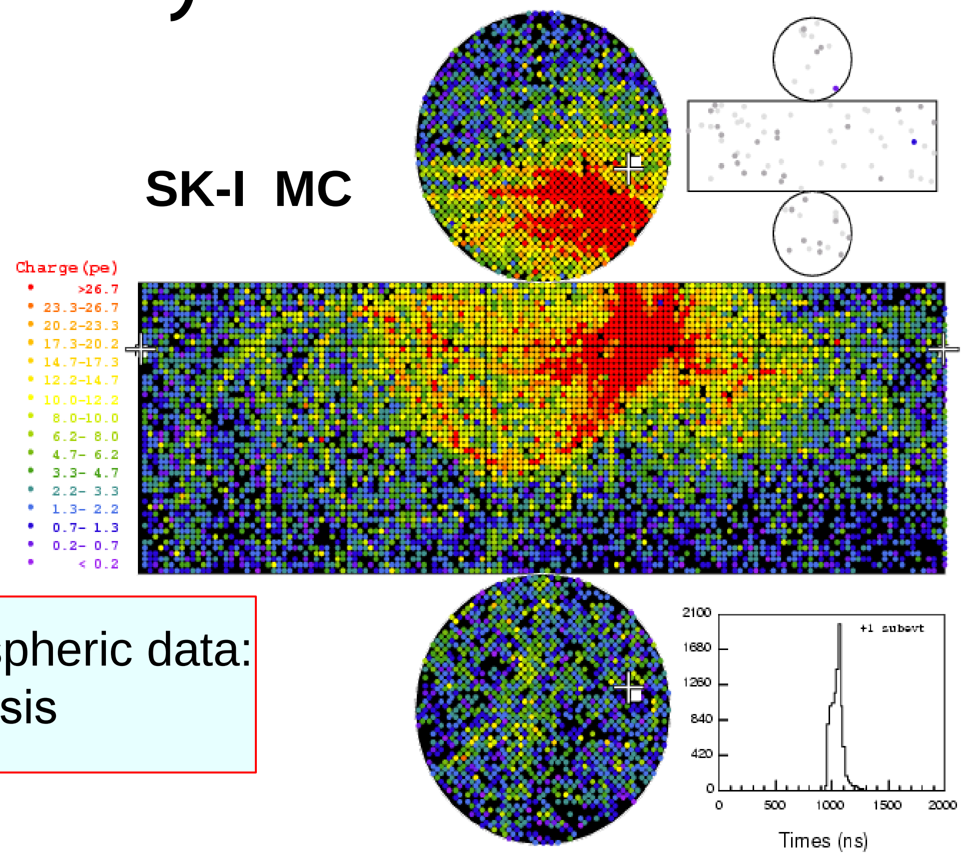
ν_τ Events at Super-K



Energy Threshold: 3.5 GeV

- Many light-producing particles
- Most events are deep inelastic scattering (DIS) interactions

- Complicated event topology makes identification of the leading lepton difficult
  - Use a Neural Network
- Negligible primary flux
  - Observed tau events must be oscillation induced

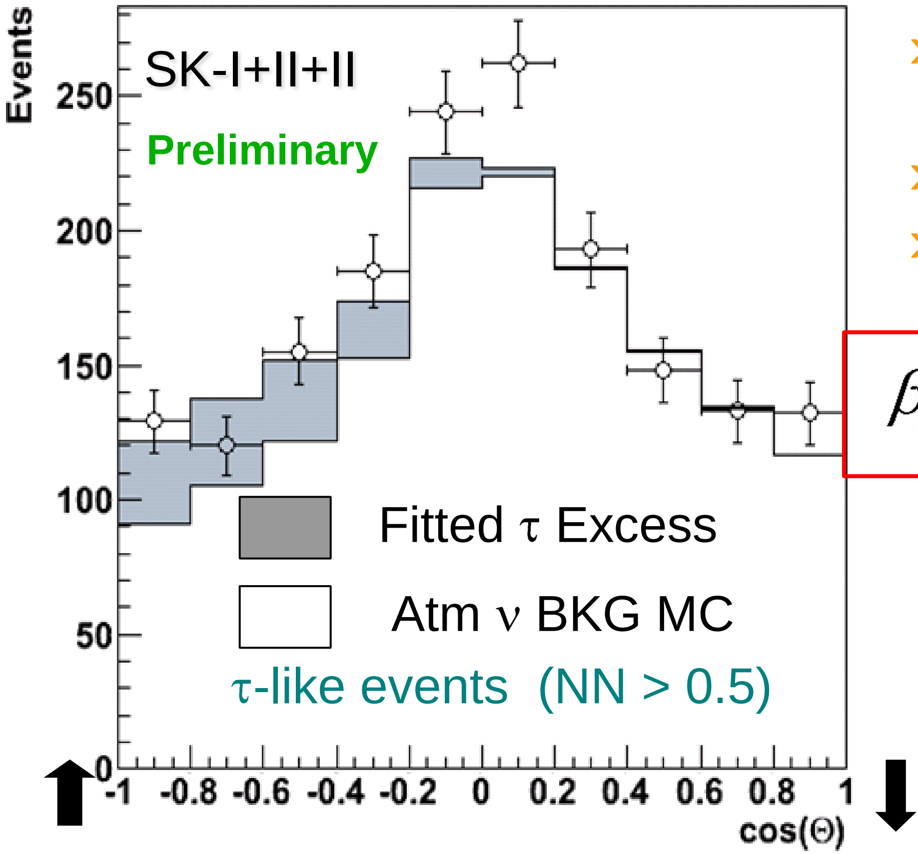


GOAL : Detect ν_τ events in SK atmospheric data: test the “no tau appearance” hypothesis

Fit Results

If no τ appearance , β = 0

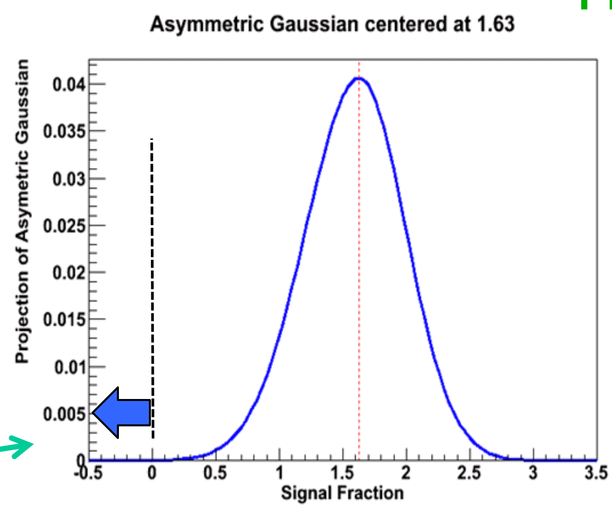
$$Data = \alpha(\gamma) \times bkg + \boxed{\beta}(\gamma) \times signal$$



- Tau signal clearly appears in upward-going region
- DIS fits to +1 σ
- τ normalization fit is 1.63 × expectation

$$\beta = 1.63 \pm 0.35_{(stat)} \; {}^{+0.10}_{-0.08}\,(sys) \; {}^{+0.02}_{-0.22}\,(3\,flav)$$

Preliminary

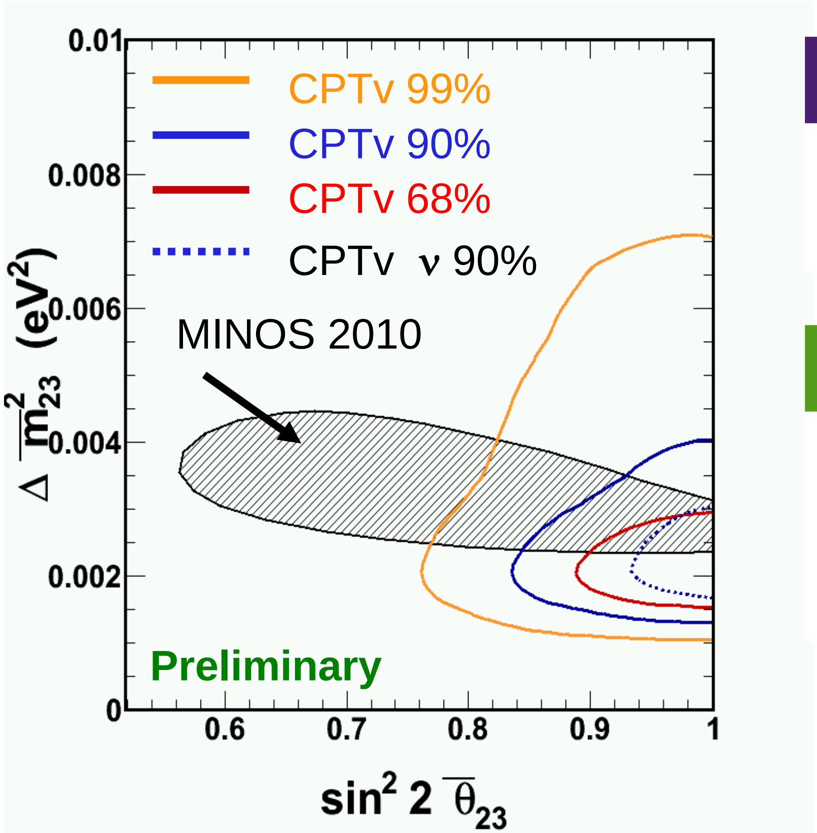


(This corresponds to 213.6 τ Events)
Measure of significance: Area under asymmetric Gaussian centered at β=1.63, for β < 0 (= no τ appearance)

SK data are ***inconsistent*** with ***no*** τ appearance at 3.8σ

Antineutrino Oscillations : CPT violation

- CPT theorem: P($\nu \rightarrow \nu$) and P($\bar{\nu} \rightarrow \bar{\nu}$) should be the same.
- Test ν oscillation or $\bar{\nu}$ oscillation separately.



SK 2806 Days

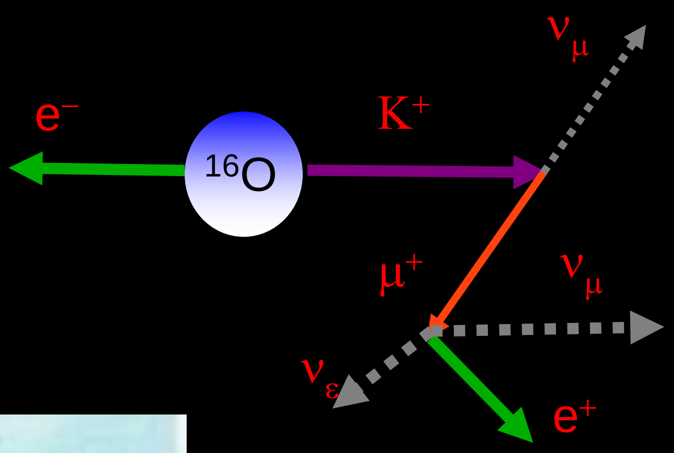
	Best Fit
Δm^2	2.1×10^{-3} eV^2
$\sin^2 2\theta$	1.0

	Best Fit
Δm^2	2.0×10^{-3} eV^2
$\sin^2 2\theta$	1.0
χ^2	468.8 / 416 D.O.F

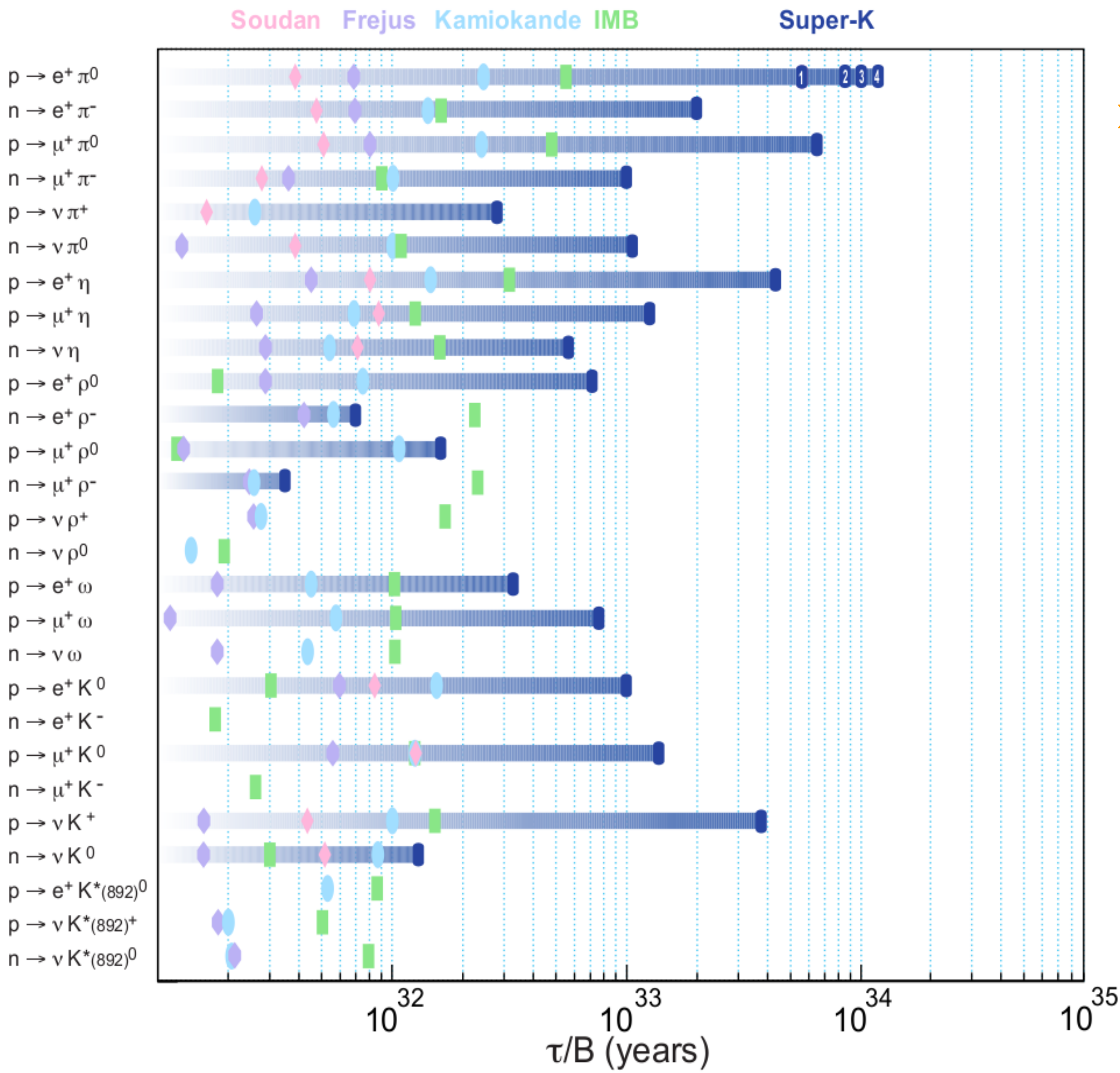
Equal neutrino and antineutrino mixing favored by the data

- No evidence for CPT violation in SK atmospheric data
- Field theories are still safe...

Search for Rare Particles and Processes



Nucleon Decay Limits, 2010

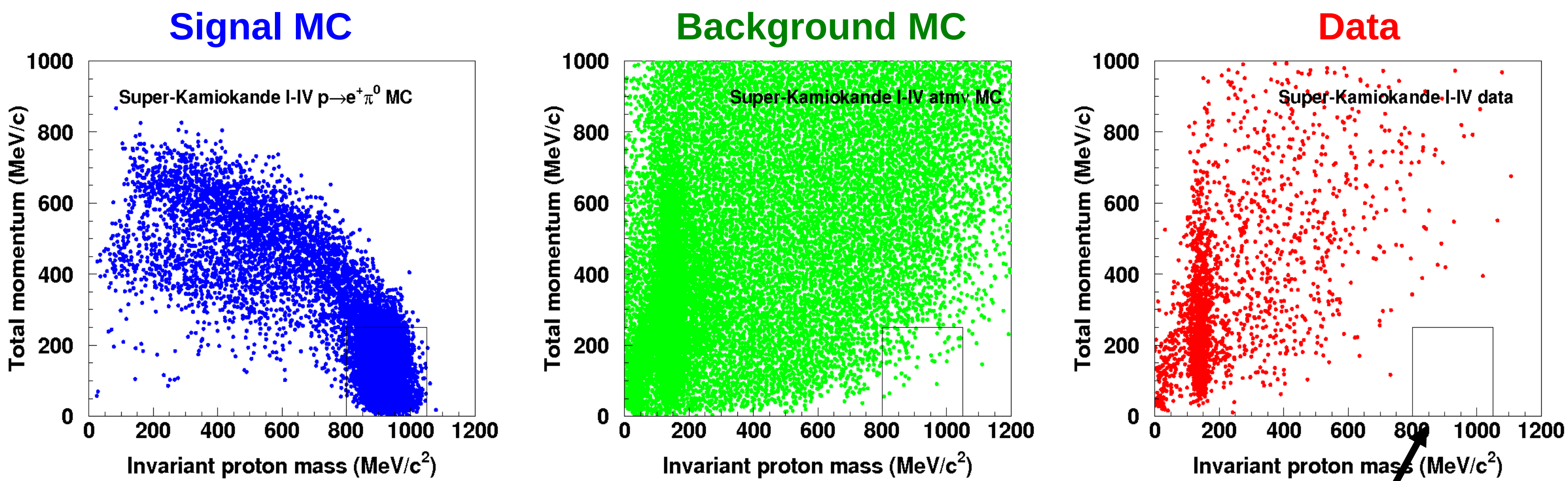


» Proton is stable in the standard model

» GUT model, Super-Symetric Models allow proton decay, but predict many different channels (and lifetimes!)

Super-K fiducial volume:
7.5×10^{33} protons
6.0×10^{33} neutrons

Search for p → e^+ + π^0 , SK-I+II+III+IV$_{\text{Preliminary}}$



p ✹ e^+ + □^{0} Cut	efficiency (%)	SK4 MC 535.2d	Data
2 or 3 Rings	73.6	1193	1117
All e-like	65.5	708.5	674
85 < □$_{mass}$ < 185 MeV	63.5	590.7	575
0 Decay electron	62.5	409.6	386
Total Mass Cut	45.0 ± 19.0	0.05	0

Still no Candidates!

Into the next decade!

SK-IV Only τ / B > 1.9 x 10^{33} yr (32.9 kton yr)

SK-I-IV combined τ / B > 1.21 x10^{34} yr (205.7 kton yr)

Fit to $p \to \nu \pi^+$, $n \to \nu \pi^0$, SK-I+II+III

Predicted by SUSY SO(10) Model
Constrained by existing SK limits (νK^+)

Phys Lett B587:105-116 (2004)

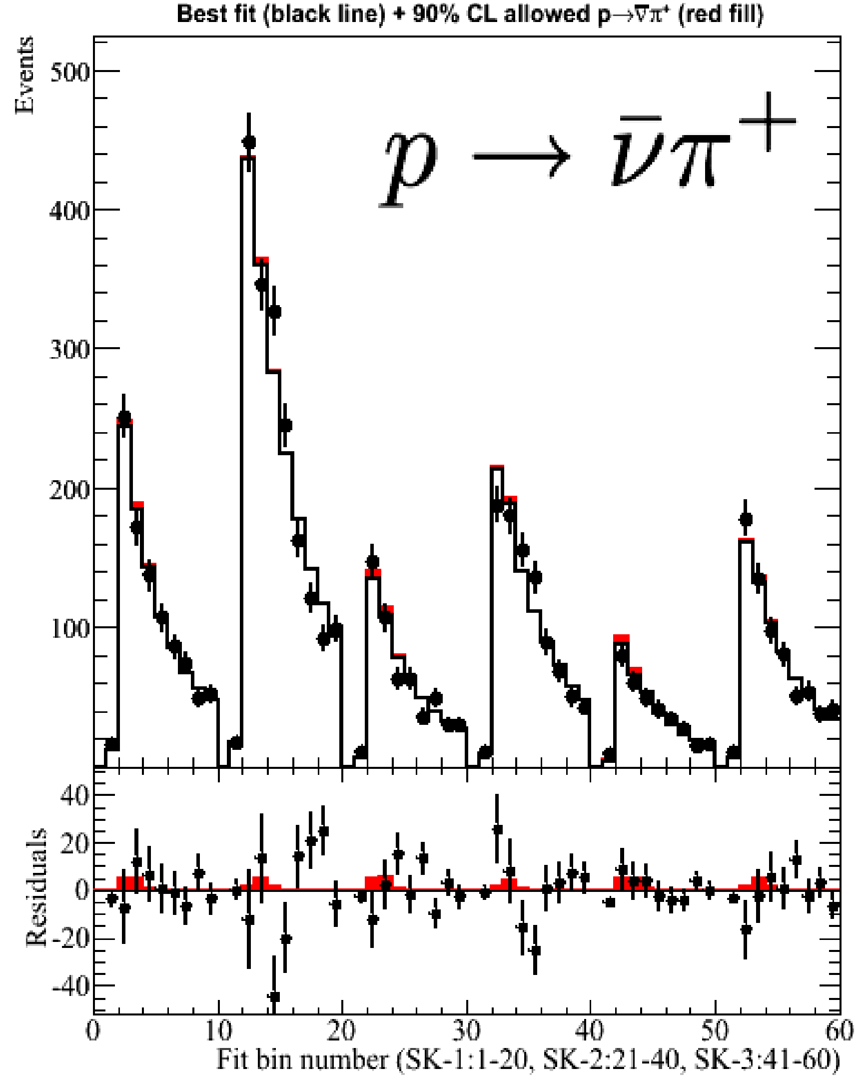
$$n \longrightarrow \bar{\nu}\pi^0$$

- Fully Contained, inside Fiducial Volume
- Two e-like rings, 85 < π^0 < 185 MeV/c^2

$$p \longrightarrow \bar{\nu}\pi^+$$

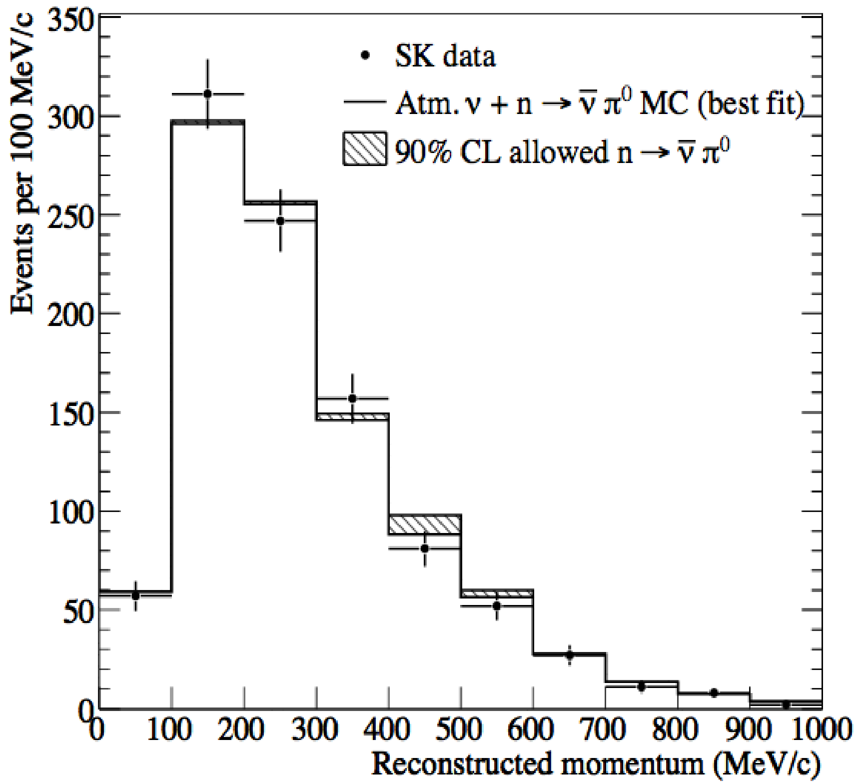
- Fully Contained, inside Fiducial Volume
- 1 μ-like ring, 0 or 1 Decay e^-

- Simple selection criteria, similar to standard atmospheric ν sample
- Fit a peak of proton decay signal in π momentum distribution, on top of the atmospheric background
  - Selection efficiency, π nuclear effects etc, are included as systematic errors



Update Best Fit and Allowed Excess

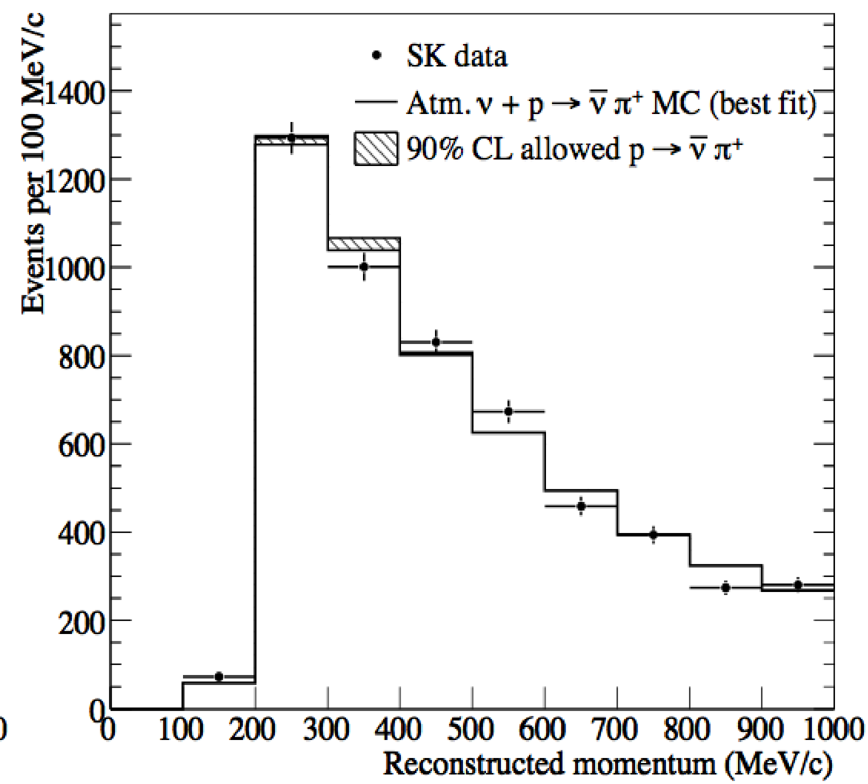
$n \rightarrow \bar{\nu}\pi^0$



SK-1+2+3 90% CL lifetime limit

$$\frac{\tau}{B_{n\rightarrow\bar{\nu}\pi^0}} > 1.1 \times 10^{33} \text{ years}$$

$p \rightarrow \bar{\nu}\pi^+$

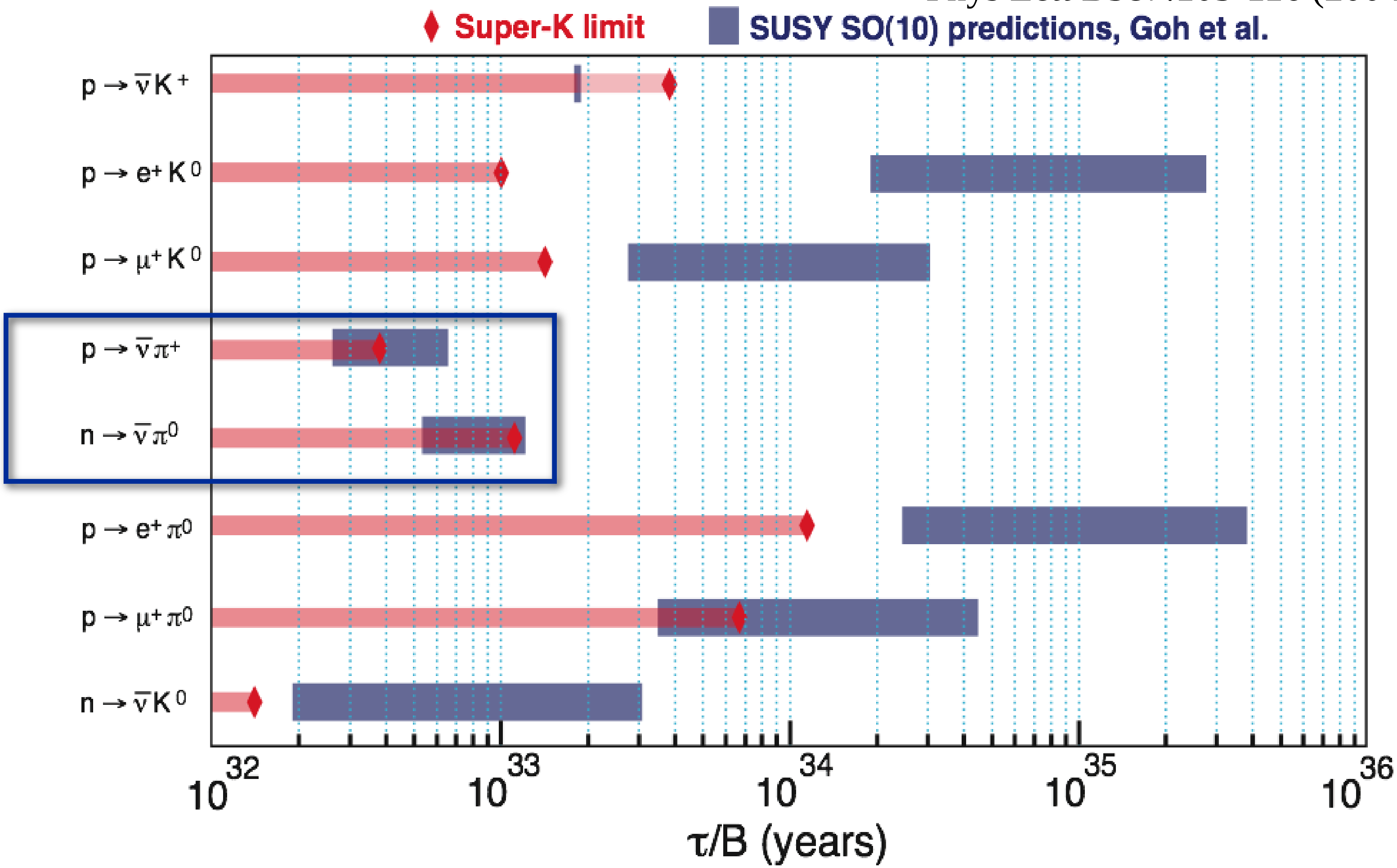


SK-1+2+3 90% CL lifetime limit

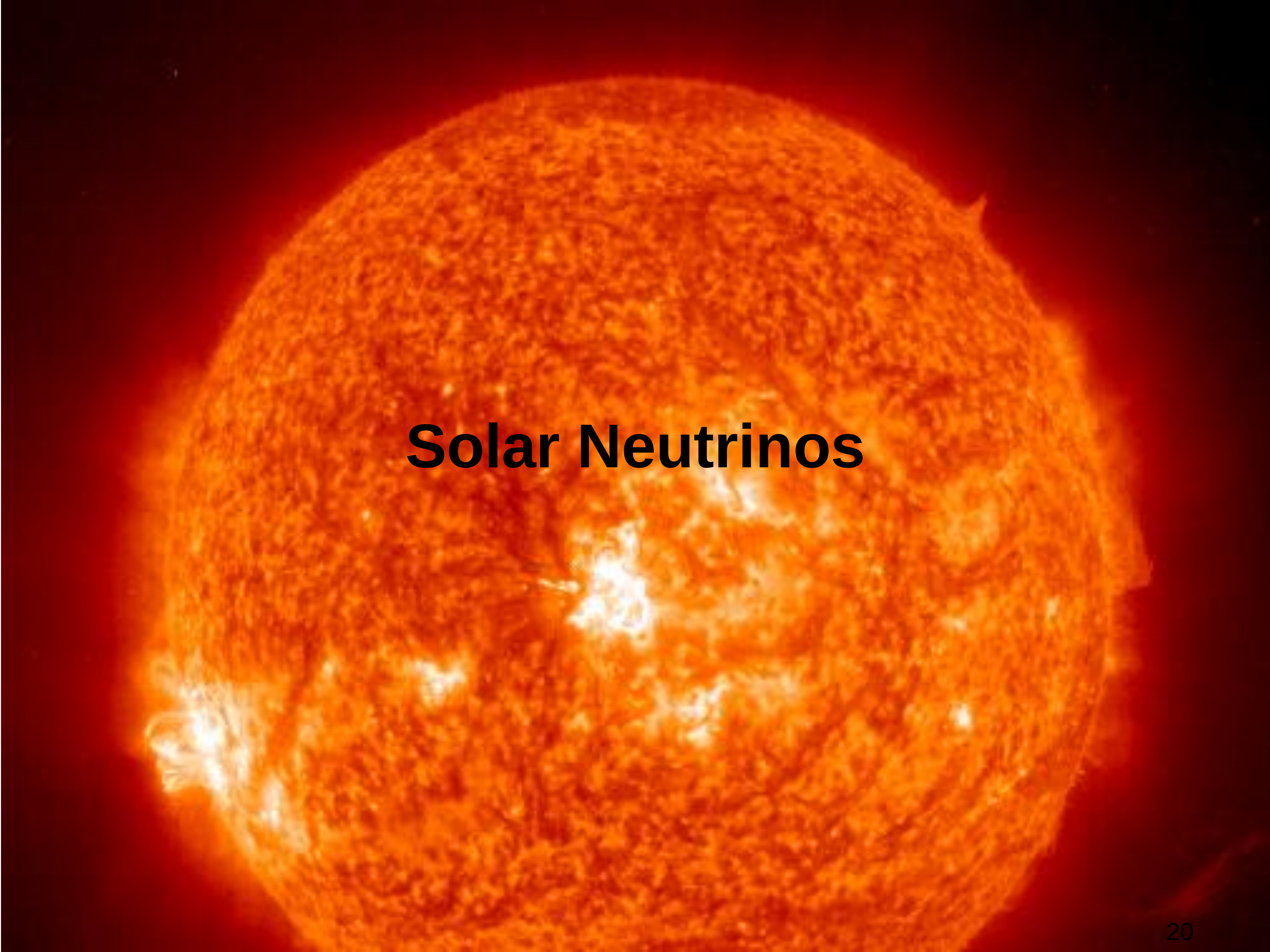
$$\frac{\tau}{B_{p\rightarrow\bar{\nu}\pi^+}} > 3.9 \times 10^{32} \text{ years}$$

Comparison with an SO(10) Model

Phys Lett B587:105-116 (2004)

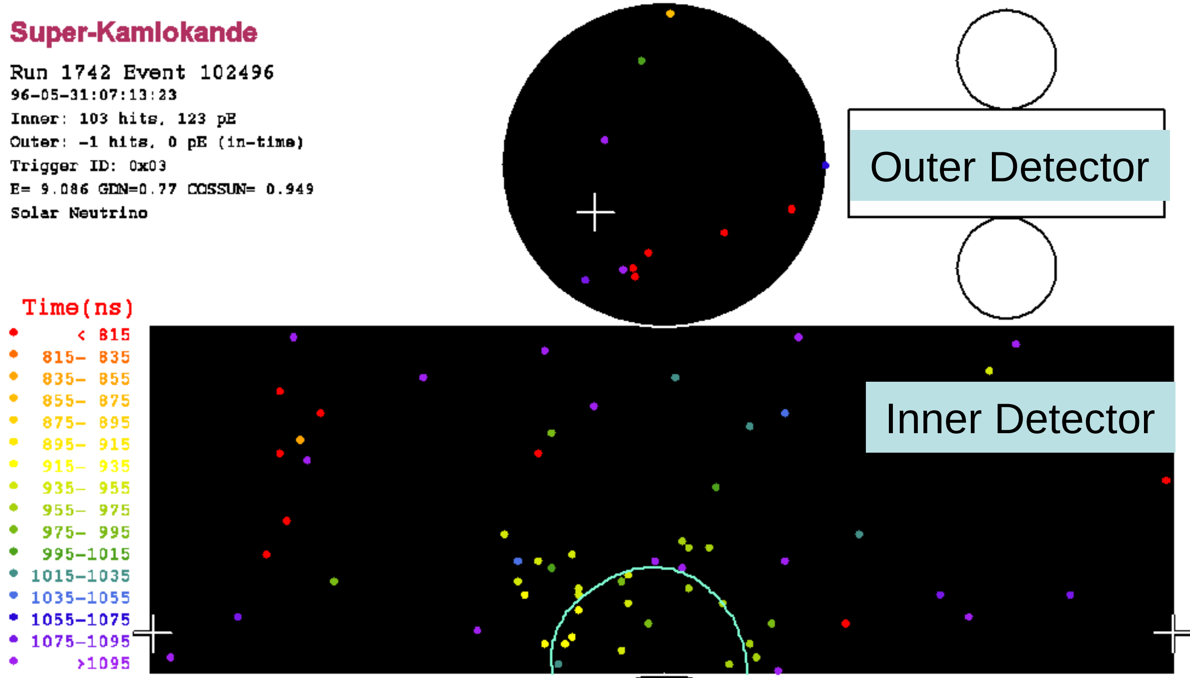


- Super-K data are providing strong constraints to these models



Solar Neutrinos

Typical low-energy event



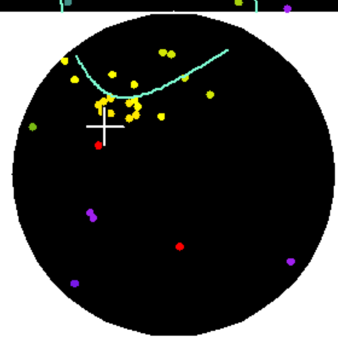
$\nu + e^- \to \nu + e^-$

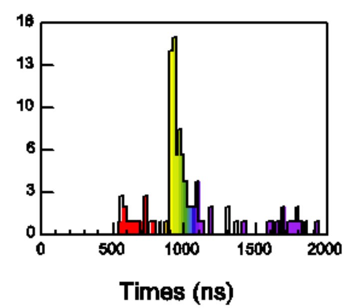
(for solar neutrinos)

- Timing information
  ➡ vertex position
- Ring pattern
  ➡ direction
- Number of hit PMTs
  ➡ energy

(color: time)

E_e = 9.1MeV
$\cos\theta_{sun}$ = 0.95





~6 hits / MeV
(SK-I, III, IV)

Resolution (for 10MeV electrons) (software improvement)

SK-I: Energy: 14% Vertex: 87cm Direction: 26°

SK-III: Energy: 14% Vertex: 55cm Direction: 23°

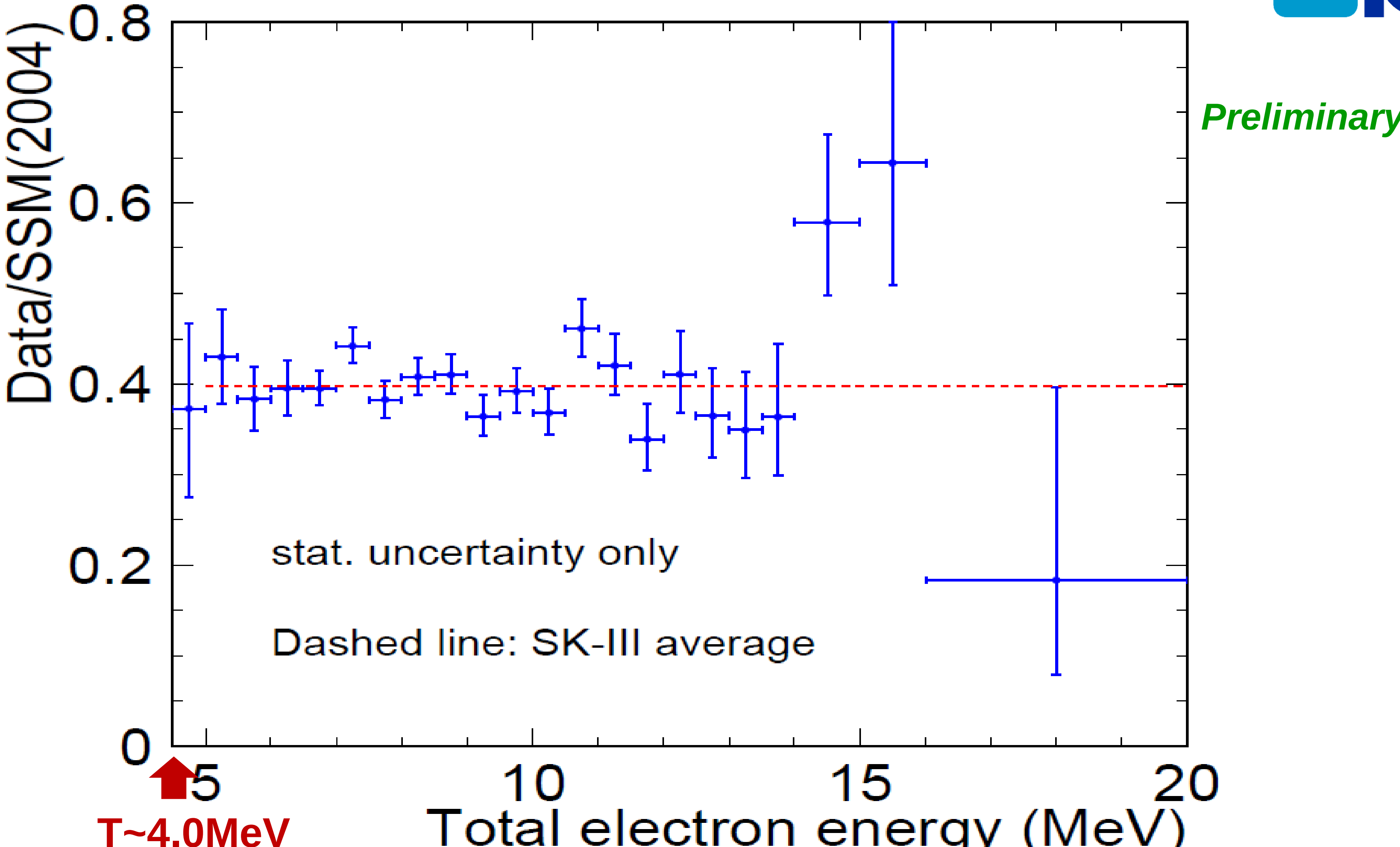
SK-III solar neutrino results

- Total live time : 548 days, $E_{total} \geq 6.5$ MeV
  289 days, $E_{total} < 6.5$ MeV
- Energy region: E_{total}=5.0-20.0MeV
- ^{8}B Flux: 2.32+/-0.04(stat.)+/-0.05(syst.) (x10^{6}/cm^{2}/s)
  - SK-I: 2.38+/-0.02(stat.)+/-0.08(syst.)
  - SK-II: 2.41+/-0.05(stat.)+0.16/-0.15(syst.)

    (SK-I,II were recalculated using the Winter06 ^{8}B spectrum)
  - SK-III official: 2.32 ± 0.04(stat.) ± 0.05(syst.)
  - SK-IV: 2.28 ± 0.04 ***Preliminary***
- Day / Night ratio:

$$A_{DN} = \frac{(\Phi_{Day} - \Phi_{Night})}{(\Phi_{Day} + \Phi_{Night})/2} = -0.056 \pm 0.031(\mathrm{stat.}) \pm 0.013(\mathrm{syst.})$$

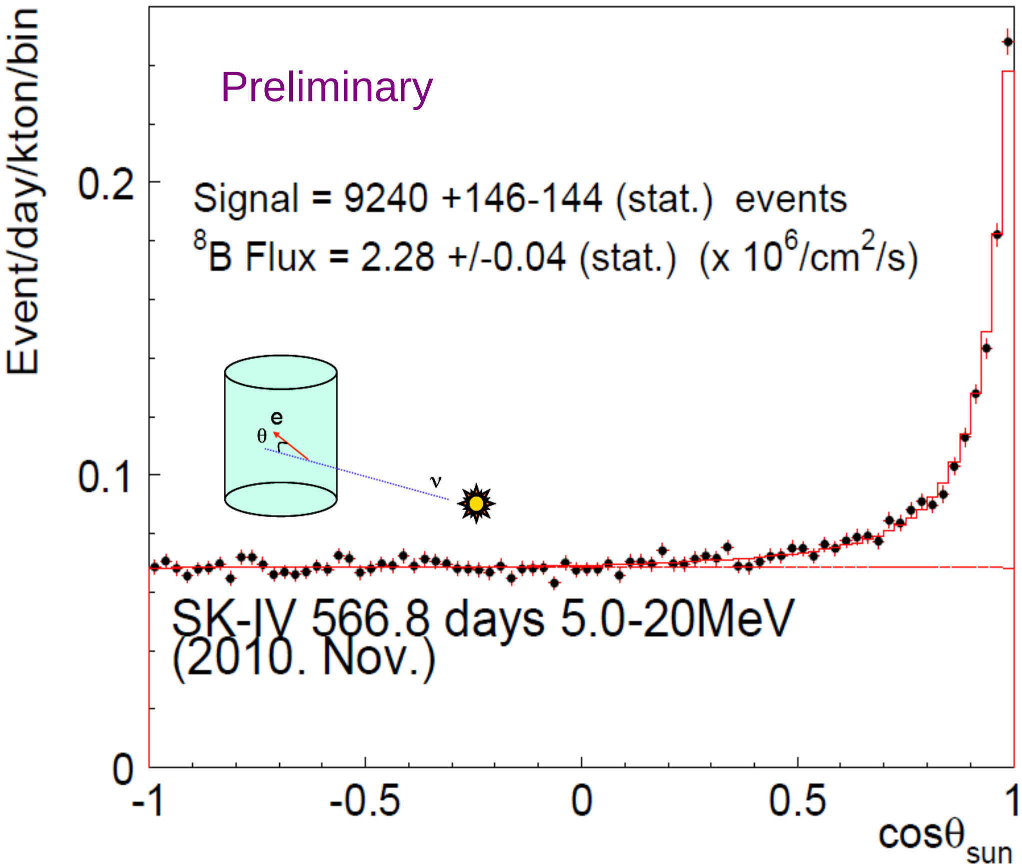
SK-III ^{8}B energy spectrum



- Consistent with no distortion

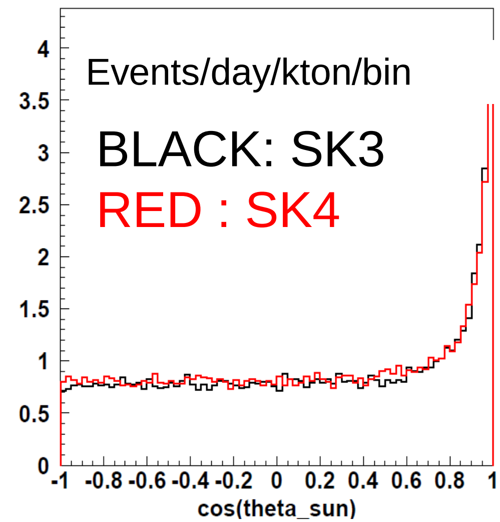
(E_{total}=4.5-5.0MeV data not used in the oscillation analysis)

SK-IV ^{8}B Flux **567 days**



SK-IV
Flux 2.28±0.04 (10^6/cm^2/s)

SK-III official:
2.32±0.04±0.05 (10^6/cm^2/s)



- Fluxes in SK-IV are consistent with those from SK-III
  - SK-IV data looks good so analysis under way
  - Following oscillation analyses are for SK-I+II+III

Oscillation Analysis Data Set and Inputs

- SK
  - SK-I 1496 days, spectrum 5.0-20MeV + D/N : E ≥ 5.0MeV
  - SK-II 791 days, spectrum 7.0-20MeV + D/N : E ≥ 7.5MeV
  - SK-III 548 days, spectrum 5.0-20.0MeV + D/N : E ≥ 5.0MeV

- SNO
  - CC flux (Phase-I & II & III)
  - NC flux (Phase-III & LETA combined) ($= 5.14 \pm 0.2 \times 10^{6} cm^{-2}s^{-1}$)
  - Day/Night asymmetry (Phase-I & II)

- Radiochemical : Cl, Ga
  - Ga rate: 66.1+/-3.1 SNU (All Ga global) , PRC**80**, 015807(2009)
  - Cl rate: 2.56+/-0.23 , Astrophys. J. **496** (1998) 505

- Borexino
  - ^{7}Be rate: 48 +/- 4 cpd/100tons, PRL**101**, 091302(2008)

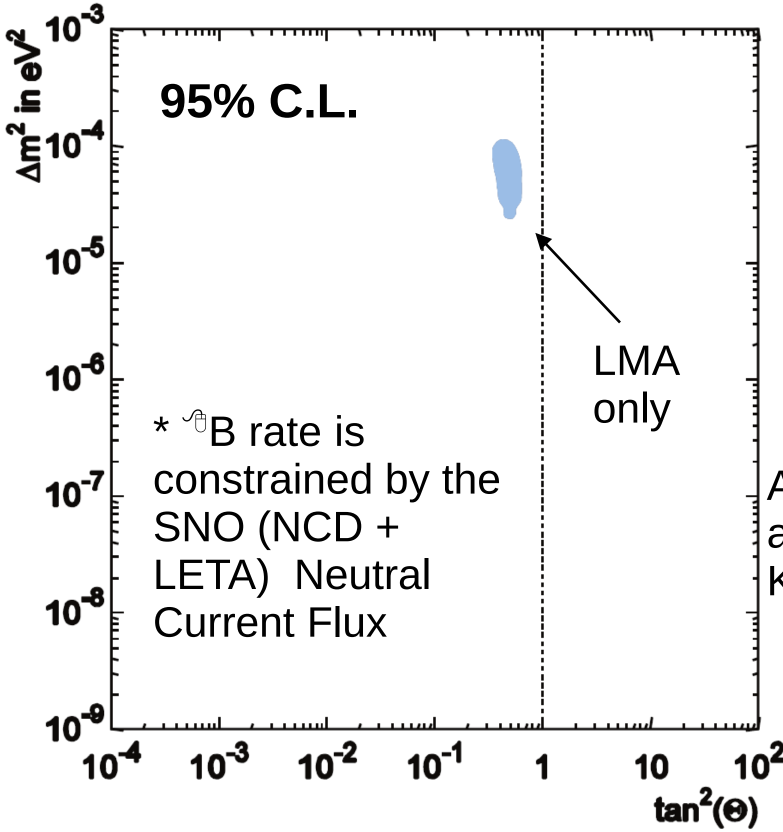
"Global Analysis" Data

- KamLAND : 2008

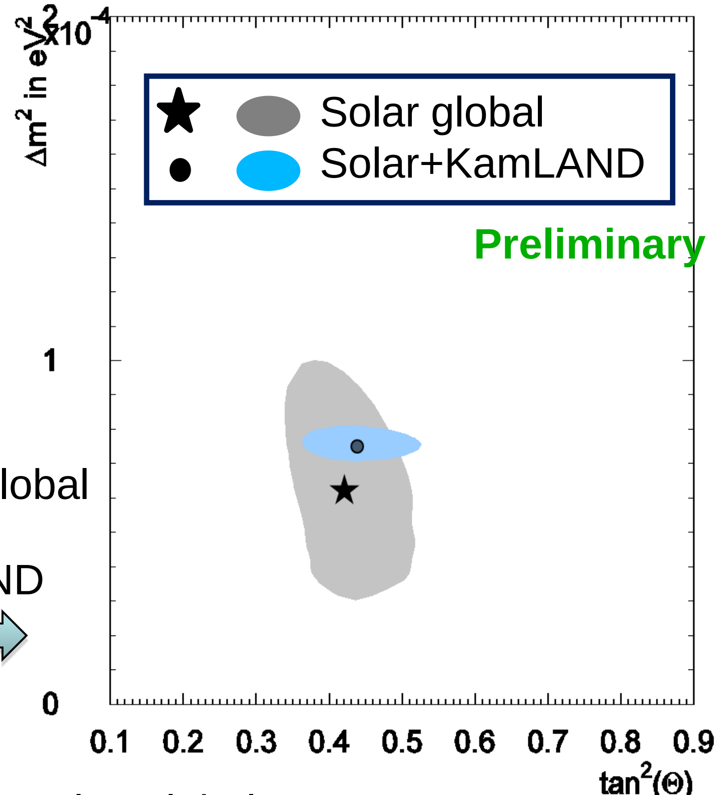
- ^{8}B spectrum : Winter(2006)

Items in red are updates since the SK analysis published in 2008 (PRD **78**, 032002)
(New analysis: in press)

Two-Flavor analysis of SK-I+II+III w/ Flux Constraint



Add in global and KamLAND



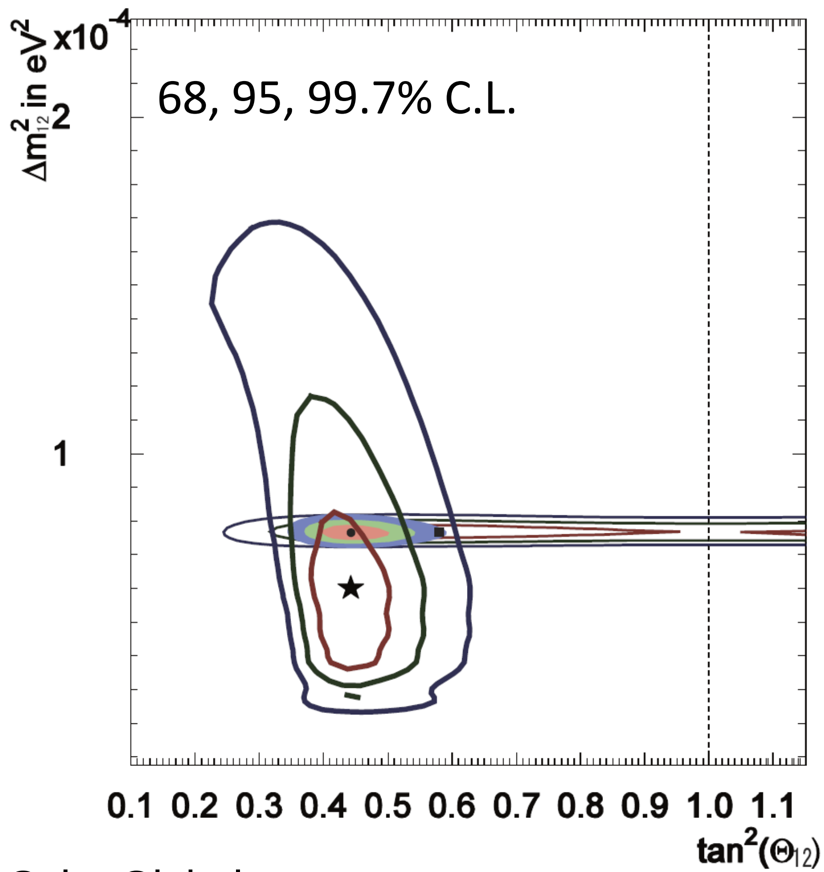
Solar Global + KamLAND

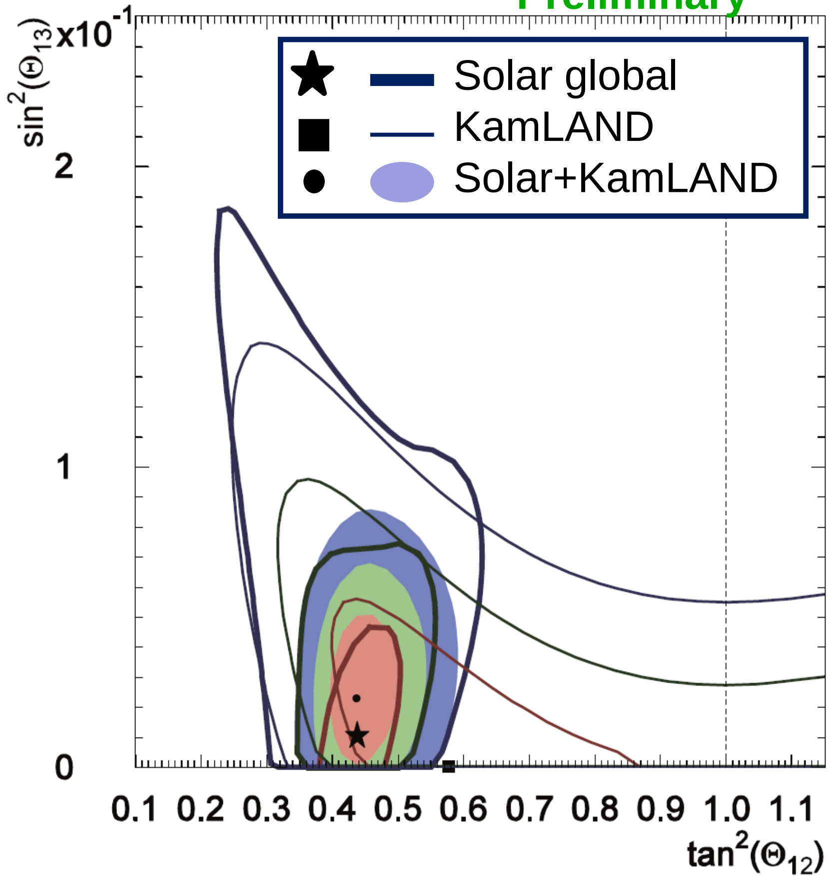
Min χ^2 = 48.8
$\Delta m^2 = 6.1\times10^{-5}$ eV^2
$\tan^2\theta = 0.48$
$\Phi_{B8} = 0.89\times \Phi_{B8,SSM}$

Min χ^2 = 57.7
$\Delta m^2 = 7.6\times10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\Phi_{B8} = 0.89\times \Phi_{B8,SSM}$

Three-Flavor Analysis (including SK-I+II+III)

Preliminary





Solar Global:

$\sin^2\theta_{13}$=0.06 @95%C.L.

Solar Global + KamLAND:

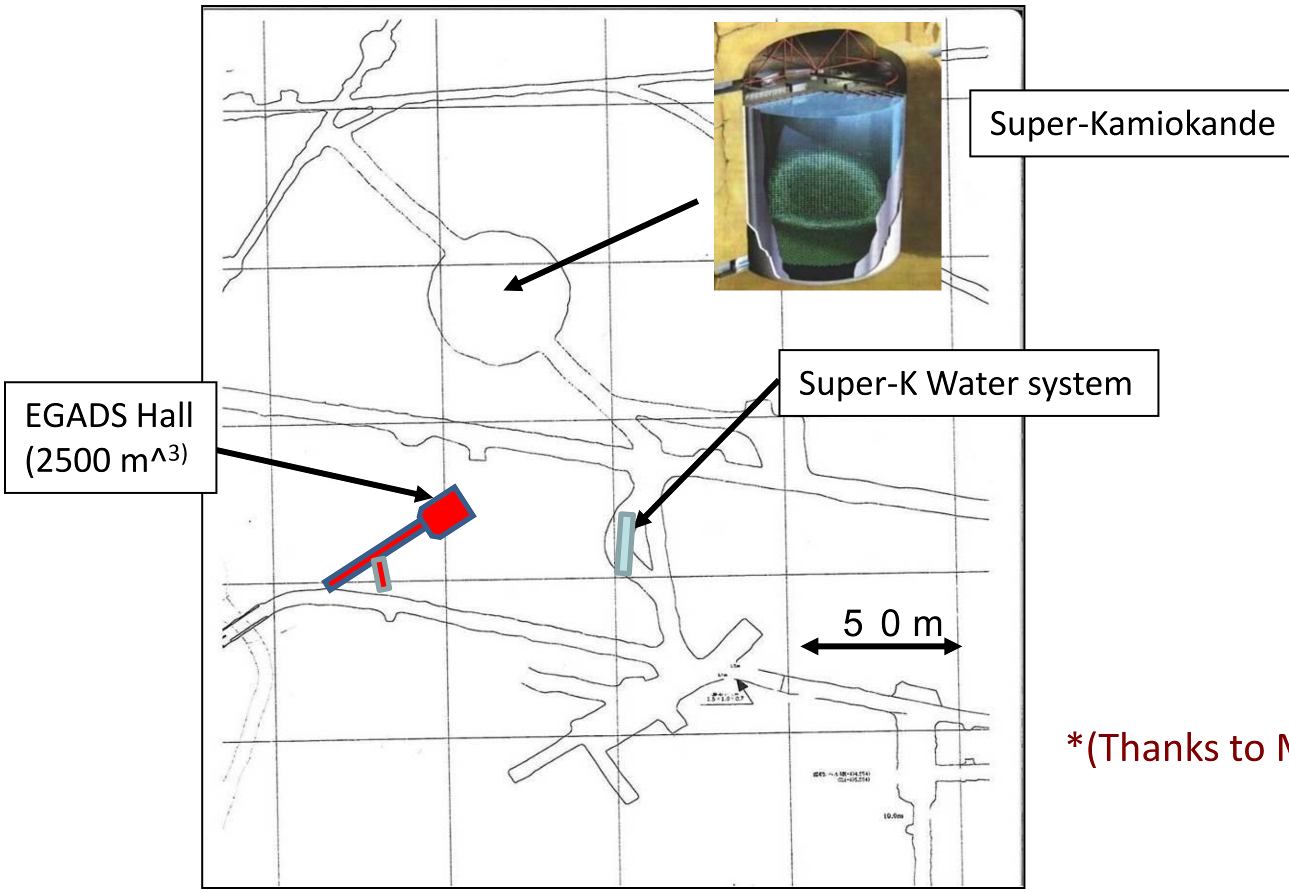
$\sin^2\theta_{13}=0.025^{+0.18}_{-0.16}$ (< 0.059 at 95%C.L.)

- In both fits, best θ_{13} is small but consistent with 0
- (arXiv:1010.0118, accepted by PRD)

EGADS – Evaluating Gadolinium's Action on Detector Systems*

Adding Gd to Super-K water would allow efficient antineutrino tagging [see Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

A dedicated Gd test facility has been built to explore feasibility. 200-ton scale R&D effort underway now (M. Vagins et al)



*(Thanks to Mark Vagins for slides)

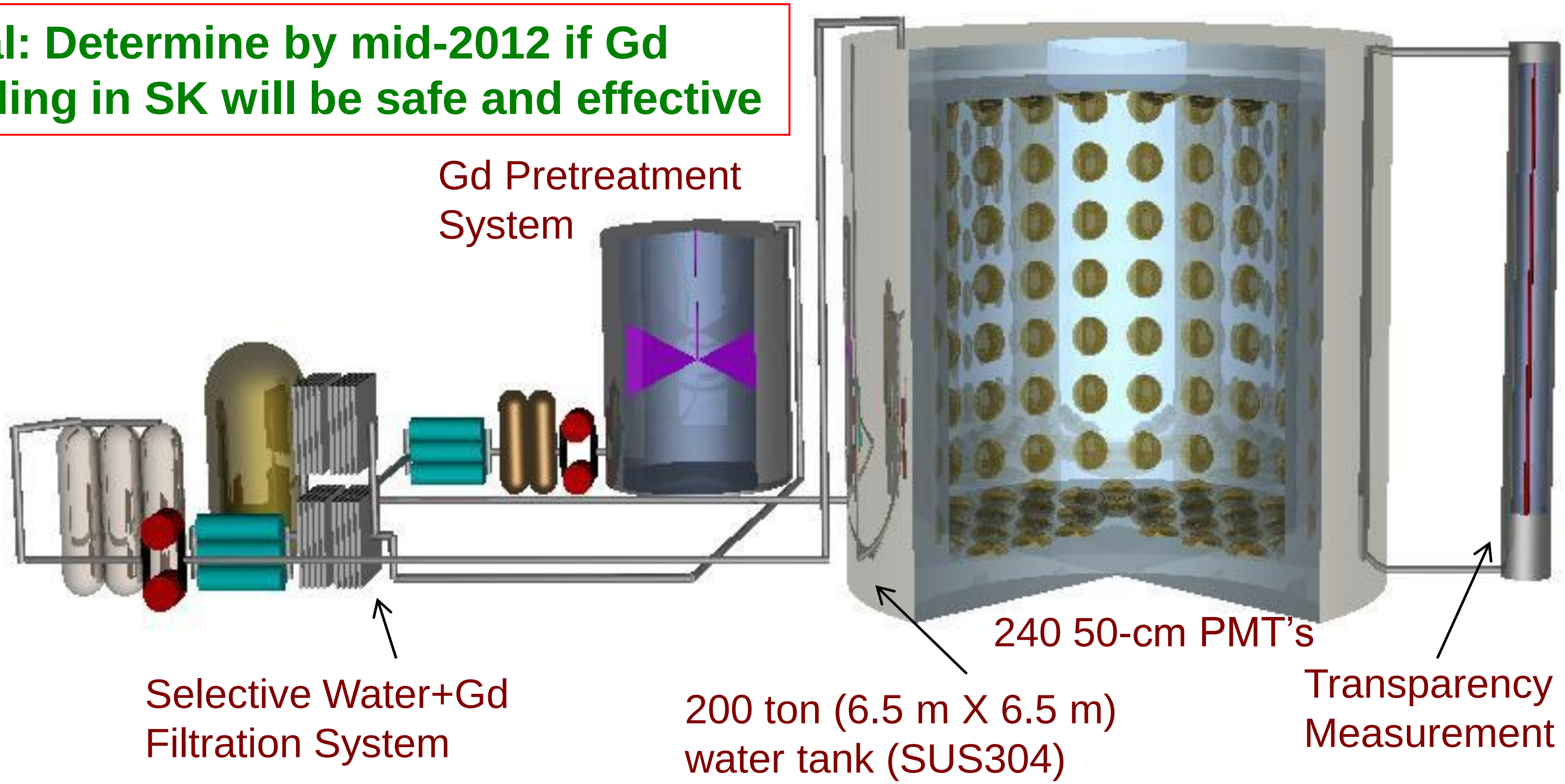
EGADS Facility

Excavation of new underground experimental hall, construction of stainless steel test tank and PMT-supporting structure, assembly of main water filtration system (completed in 2010)

Tube prep, mounting of PMT's, installation of electronics and DAQ computers (2011)

2011-13: Experimental program, long-term stability assessment, material aging studies in Japan, and transparency and water filtration studies in the US

Goal: Determine by mid-2012 if Gd loading in SK will be safe and effective



EGADS Schedule

2009-10: Excavation of new underground experimental hall,
construction of stainless steel test tank and
PMT-supporting structure (all completed, June 2010)

2010-11: Assembly of main water filtration system (completed),
tube prep, mounting of PMT's, installation
of electronics and DAQ computers

2011-13: Experimental program, long-term stability assessment

At the same time, material aging studies will be carried out in Japan, and transparency and water filtration studies will continue in the US

The goal is to be able to state conclusively whether or not gadolinium loading of Super-Kamiokande will be safe and effective.

Target date for decision = mid-2012

Supernova Relic Neutrinos

Supernova Relic Neutrinos (*SRN*)

Diffuse neutrino signal from all past supernovae.

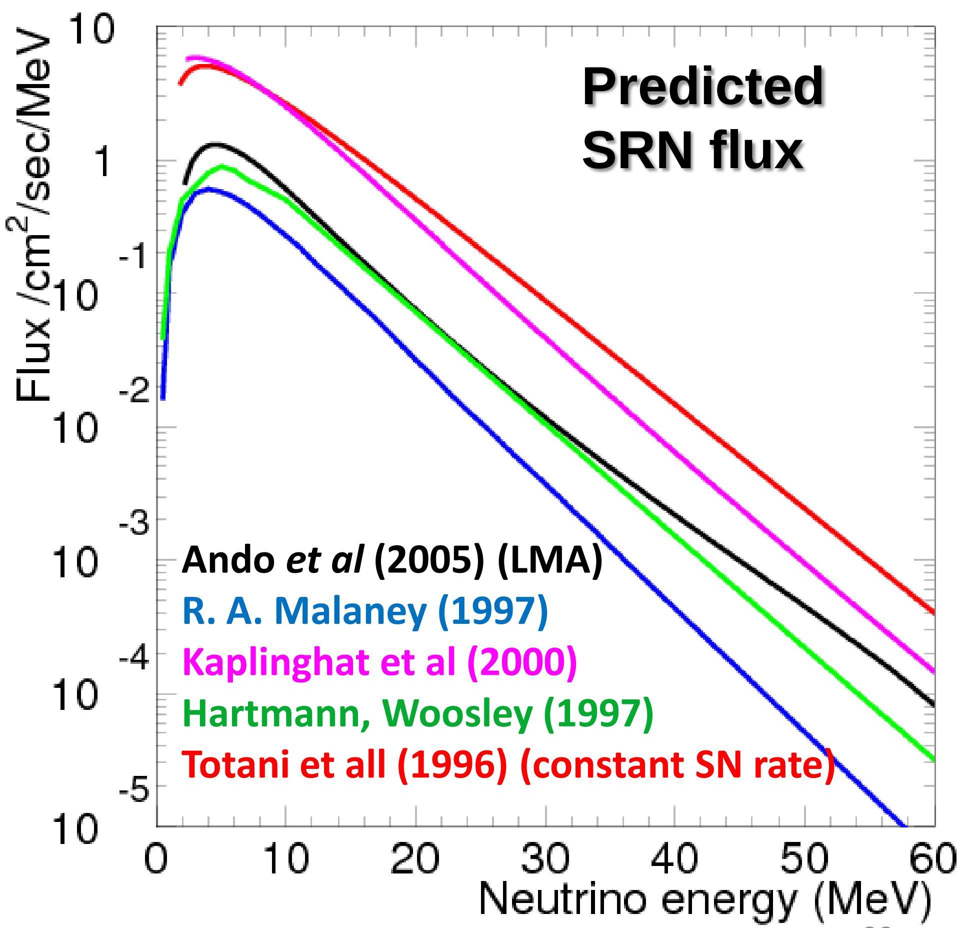
Not yet detected…hard to extract from spallation and atmospheric ν backgrounds!

Expected number of SRN events in SK

10-30MeV: 0.8 -5.0 events/year/22.5kton

16-30MeV: 0.5 -2.5 events/year/22.5kton

18-30MeV: 0.3 -1.9 events/year/22.5kton



Motivation

SRN flux tells us about the SN rate in galaxies, and cosmic star formation history

2003 SK-I result:
M. Malek, et al, PRL 90, 061101
Flux **< 1.2 /cm² /sec**

Improvements in new SK SNR analysis*

Lower threshold

From 18 → 16 MeV

(going further very difficult, due to many different long half-life spallation products 10~15 MeV)

More data

Include SK-II, -III

Reducible Backgrounds

Nuclear spallation from cosmic μ's

Solar neutrinos

Radioactive backgrounds

Cosmic ray muons, decay electrons

Pions from neutrino interactions

Electronics effects

Greatly reduced analysis inefficiencies

SPALLATION cut using correlation to cosmic ray muons

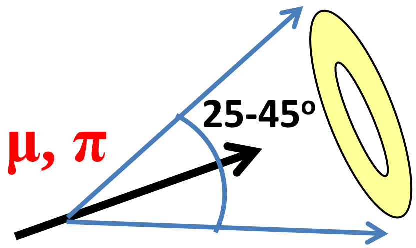
- New method allows 3-D spatial correlation, muon categorization
- Stricter cut < 18 MeV

SOLAR events cut by correlation to solar direction

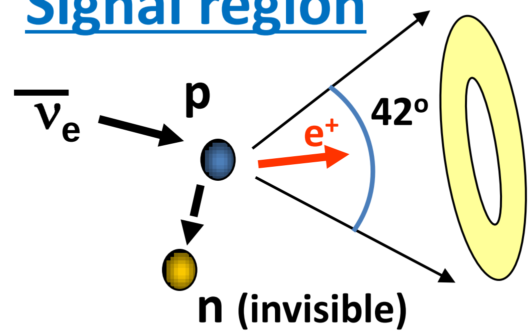
- New technique estimates multiple scattering, which dominates angular resolution
- Optimized in 1 MeV bins using MC, better reduction

*(Thanks to Kirk Bays for slides)

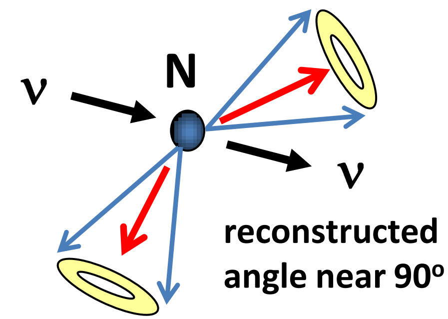
Low angle events



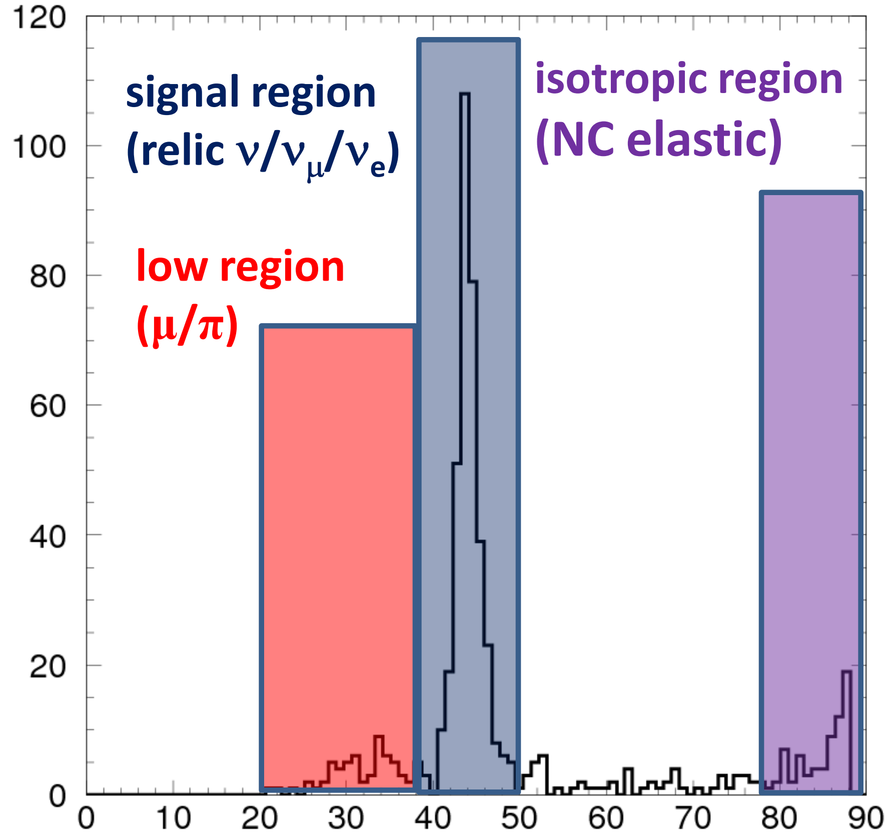
Signal region



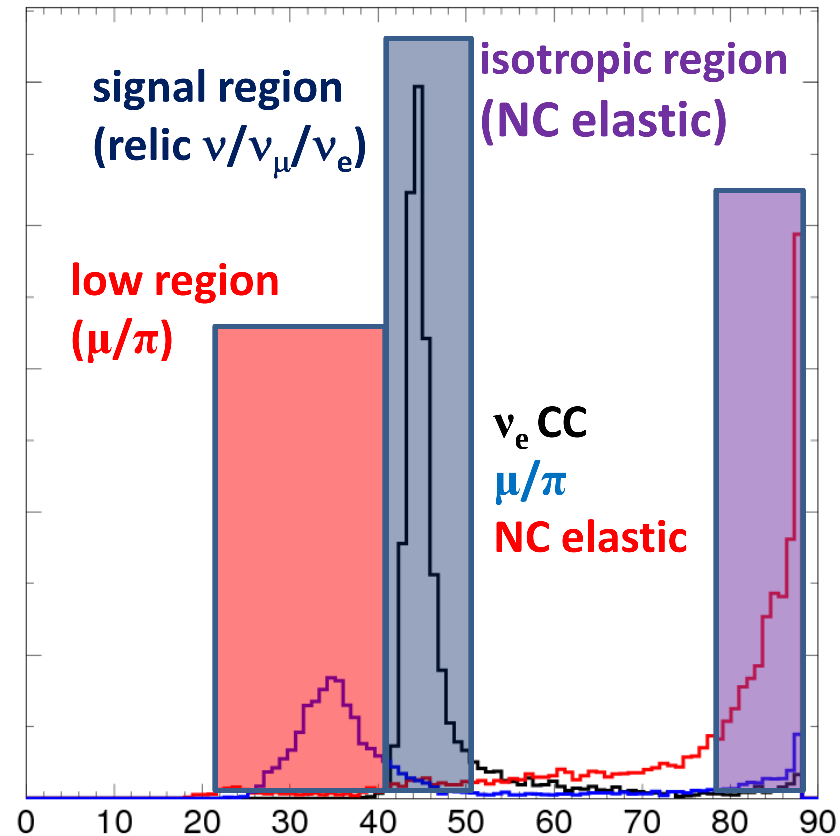
Isotropic region



SK-I/III combined final data sample



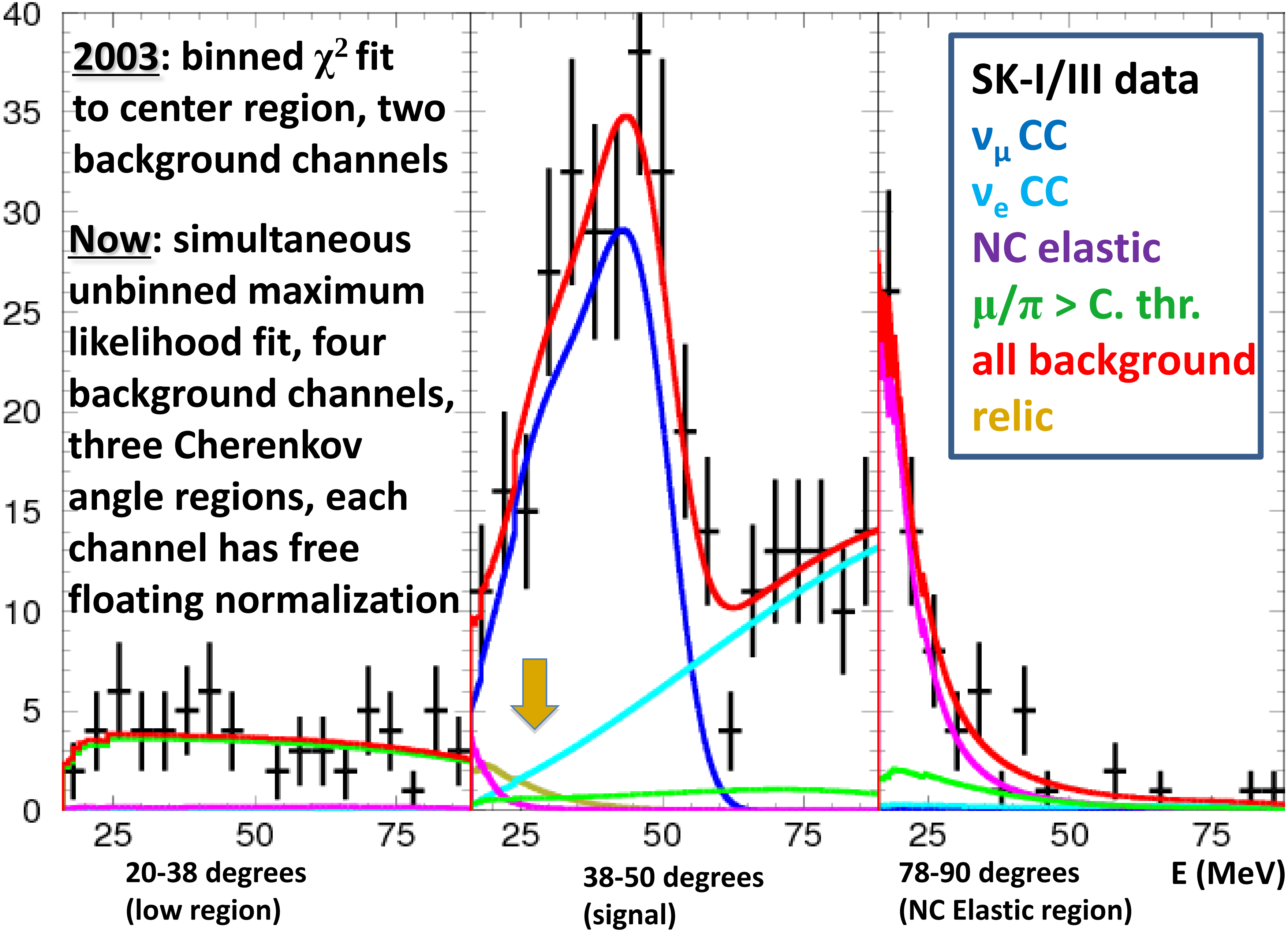
MC (without ν_μ contribution)



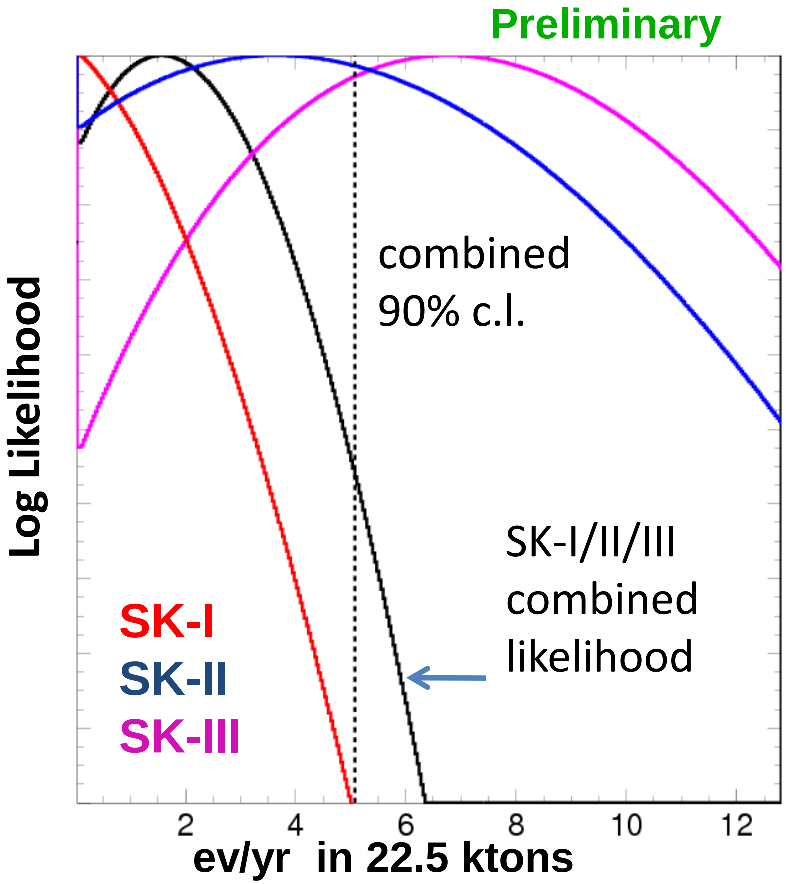
Cherenkov angle distribution degrees

2003: binned χ^2 fit to center region, two background channels

Now: simultaneous unbinned maximum likelihood fit, four background channels, three Cherenkov angle regions, each channel has free floating normalization



Combined Fit



combined 90% c.l.:

< 5.1 ev / yr / 22.5 ktons interacting

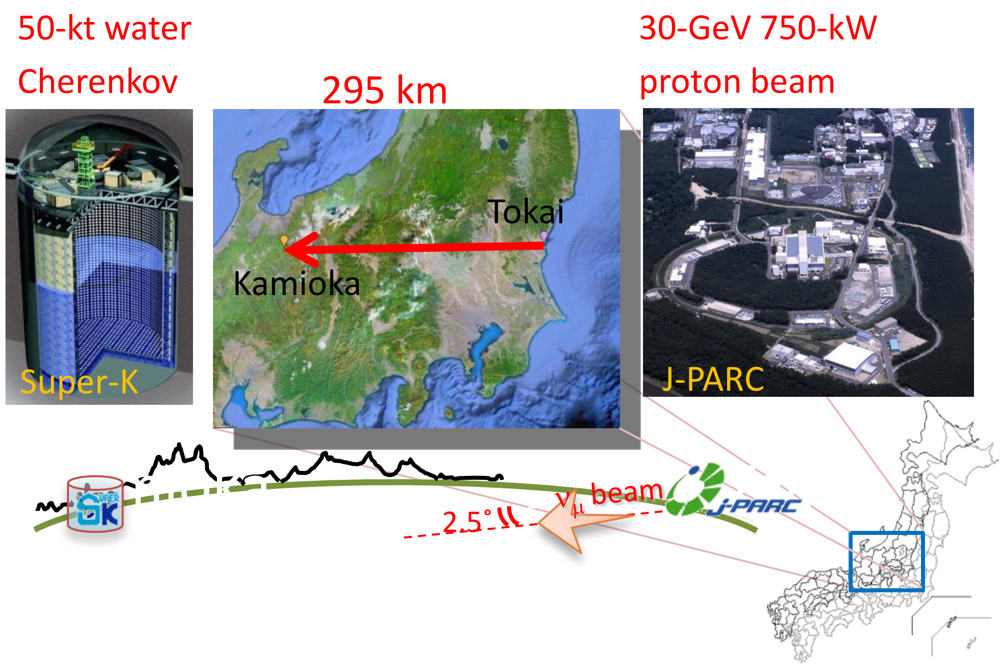
< 2.7 $/cm^2/s$ (>16 MeV)

< 1.9 $/cm^2/s$ (scaled to >18 MeV)

Comparison to Published	$/cm^2/s$ >18 MeV
Published limit	1.2
cross section update to Strumia-Vissani	1.2 → 1.4
Gaussian statistics → Poissonian statistics in fit	1.4 → 1.9
New SK-I Analysis: E_{THRESH} 18 → 16 MeV ε = 52% → 78 % (small statistical correlation in samples) improved fitting method takes into account NC	1.9→1.6
New SK-I/II/III combined fit	1.6 → 1.9

Last but not least…

- Super-Kamiokande is the far detector for the **T2K** long baseline experiment!
- For latest news, see talk by T. Kobayashi tomorrow
  - (see also: posters 91~93 on T2K)



Summary

- SK-IV is running with the lowest energy threshold ever!
  - 100% efficiency at E_{total}~ 4.5MeV
  - First results on solar neutrinos from SK-IV
- Full 3-flavor atmospheric ν oscillation results from SK-I,II,III data
- 3-flavor solar ν oscillation results from SK-I,II,III data: PRD soon
- New results approaching publication:
  - SRN analysis with SK-I,II,III
  - Tau analysis with SK-I,II,III
- EGADS = R&D for Gd in SK is underway.
  - Results expected in 2012
- Extremely high livetime efficiency for T2K beam

Special thanks to Kirk Bays, Mike Dziomba, Ed Kearns, Yasuo Takeuchi, Roger Wendell and Mark Vagins for many of the slides used here